

PM Production and Applications of HSS

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ABSTRACT

It is now over 35 years since industrial production started of semi-finished products, components and cutting tools based on powder metallurgical high speed steel. The first PM production of HSS was based on hot isostatic pressing and consolidation of inert gas atomized powders, normally followed by hot forging of thehipped billets. The development and market acceptance has since been quite successful of this high performance and high-tech material. This method is still by far the dominating PM method to produce HSS and tool steels.

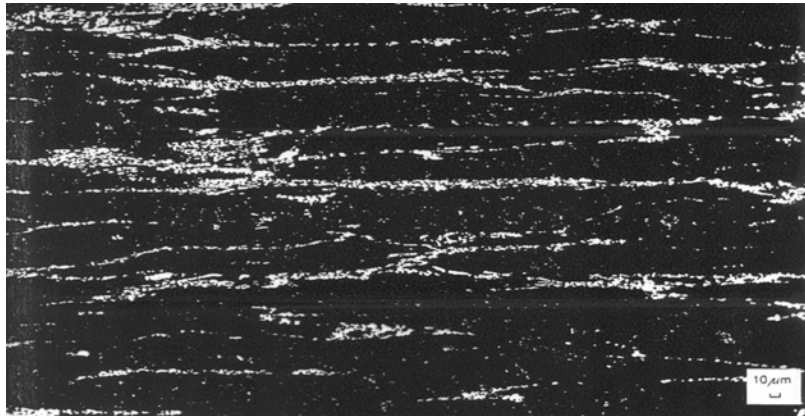
However, several different PM manufacturing methods (MIM, uniaxial pressing + sintering, rapid tooling, sprayforming) have now been developed and are now on different stages of market introduction. Large efforts have also been invested in further process and material development of PM HSS produced by inert gas atomization + hipping. This has resulted in large improvements of the functional properties of established PM high speed steel grades and introduction of new ones. Examples of such improvements are cleaner HSS with substantial less content of inclusions and new high alloyed HSS grades, often designed for specific fields of application.

HIGH SPEED STEEL BY POWDER METALLURGY

Research and development started about 1965 on powder metallurgy processing of high speed steels. The objective was to improve the functional properties and performance of HSS in demanding applications and thus increase the competitiveness of HSS versus cemented carbides primarily in machining operations. The R&D works was focused on the production of fully dense HSS billets and hot worked semi-finished products using the manufacturing route: *melting + inert gas (nitrogen) atomization + powder encapsulation + hot isostatic pressing*.

The small droplets solidify rapidly during the atomization step, which gives a fine uniform carbide microstructure in the particles. This fine microstructure can be maintained after the hot isostatic pressing and hot working operations resulting in the PM HSS: s having fine, segregation-free, uniform and isotropic microstructure. The well-known problems with coarse and severe carbide segregation in conventional cast and forged high speed steels are thus avoided in the PM HSS: s. See the comparison in figure 1.

Conventional



PM

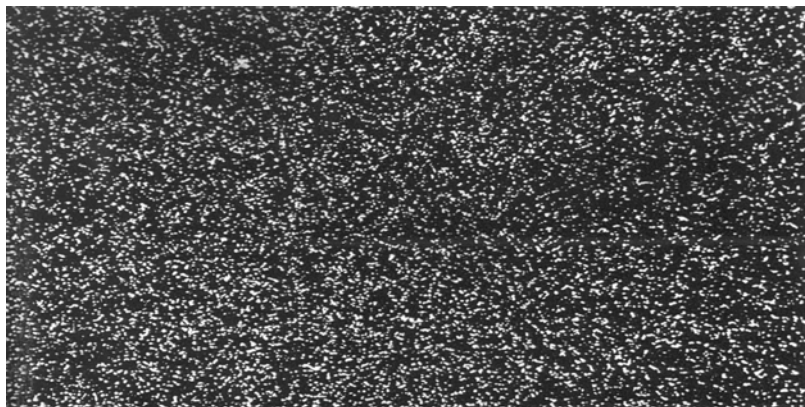


Figure 1. Microstructure of conventional HSS compared PM HSS.
(black – iron matrix, white – carbides).

It was early found that PM HSS: s exhibit several advantages as a result of the refined, homogeneous microstructure compared with their cast and wrought counterparts such as:

- no macrosegregation
- improved strength, toughness and ductility at the same hardness
- isotropic properties give less distortion at hardening of tools
- improved grindability
- improved hot workability permits higher carbide contents in the PM HSS and thus higher hardness at room and elevated temperature, which gives highly improved wear resistance
- in many cases large increase of lifetime for cutting tools. Similar increases has also been found for PM HSS and PM tool steels used for cold and hot working tools as well as for forming tools.

Figure 2 next page shows the relationship between bending strength and hardness for a number of materials including PM HSS (ASP) cast and wrought HSS and cemented carbides.

Commercialisation started in 1970 by an American (1) and a Swedish company (2). PM high speed steel and PM tool steels have now, after some incubation time achieved an important market share.

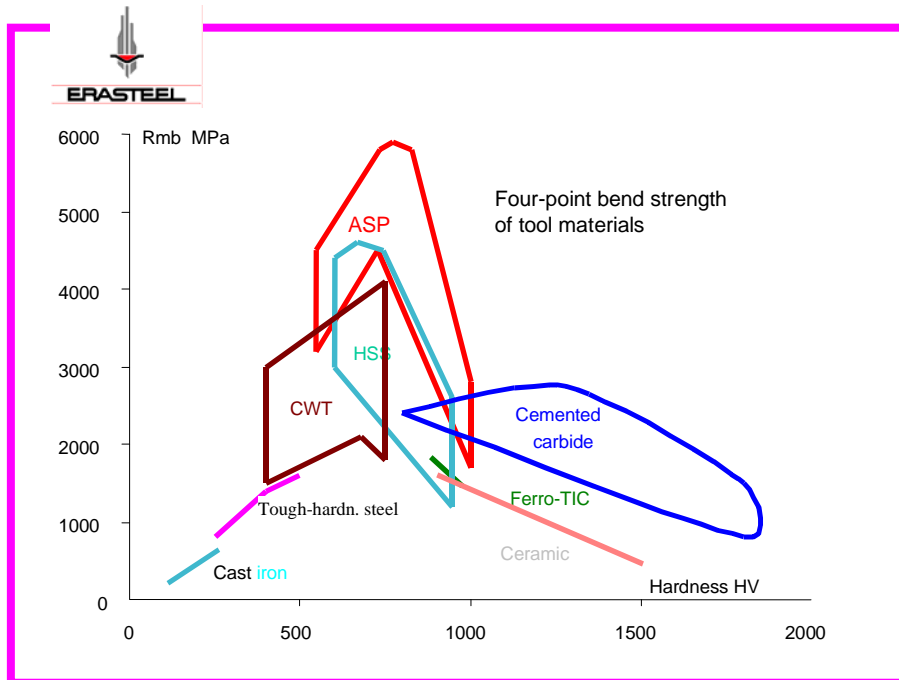


Figure 2. Relationship between bend fracture strength and hardness for HSS, tool steels, cemented carbides and ceramic materials

Numerous researchers have since mid of the 1970: s studied high temperature sintering of high speed steel powders to full density at atmospheric pressure or under vacuum. The sintering step is carried out at a temperature slightly above the solidus of the steel and thus in the two-phase region solid-liquid. This PM process is therefor often referred to as “super solidus liquid phase sintering”. The formation of small amounts of liquid phase facilitates the attainment of a pore free (or nearly pore free) microstructure.

The sintering step and temperature is highly critical – a too high sintering temperature gives an as-sintered material with unsuitable, coarse carbide microstructure, while a too low temperature results in residual porosity. The sintering window giving optimal properties is very narrow and often in the order of a few Kelvin (K). The process route is as follows: *mixing of annealed water atomized HSS powders, graphite and lubricant + uniaxial pressing in a closed die + sintering and heat treatment.*

The original objective of using this process was to produce at low cost net shape HSS cutting tools. In spite of huge R&D efforts during the last 20 years, especially in Europe, there has only been a limited market penetration of high temperature HSS machining tools. However, large volumes of HSS valve seat inserts are produced based on this process to be used in engines for passenger cars.

A vast interest arose about 20 years ago in the metal injection moulding process (MIM), which nowadays is also designated the powder injection moulding process (PIM). PIM comprises injection moulding of metallic, ceramic as well as hard metal powders. This process was rapidly developed into industrial mass production of small, complex, net shape parts of primarily stainless steel and low alloy steel.

The industrial production of HSS parts by the PIM process started several years later than for e.g. stainless steel parts. This was primarily due to production difficulties in carbon control of the as-sintered HSS parts. However, these have been solved and there are now a considerable industrial production of small, complex and wear resistant parts of high speed steel.

High speed steel billets and net shape parts are produced since many years with sprayforming also called the Osprey process. The production volumes have so far been rather small. A new, large and modern Osprey-plant has recently been taking in production by Dan Spray A/S in Denmark. The production here seems now to be more focused on high performance tool steels.

Finally, HSS tools and prototypes are now since some years manufactured by *rapid prototyping or rapid tooling by laser sintering*. The tonnage volume is limited and so far only highly marginal related to machining tools.

APPLICATION AND MARKETS FOR PM HSS

It is well known that there is a hard competition between the HSS and tool steel producers and the cemented carbide industry. There is of course also a competitive situation between conventionally produced (cast and forged) HSS and tool steels versus these steels produced by powder metallurgical methods.

However, there is virtually no competition within the PM family of processes i.e. between hot isostatic pressing (HIP), uniaxial pressing and high-temperature sintering and metal injection moulding. On the contrary, these processes complement each other in an excellent way. Figure 3 shows approximate technical – economical feasibility areas for steel products in general produced by different methods e.g. hot isostatic pressing of steel parts near net shape (NNS) and billets is feasible in a weight range between about 20 kg to 12 000 kg and in lot sizes from a single piece up to several thousand pieces. Figure 3 thus shows that products of HSS and tool steels now are manufactured industrially in the weight range 0.5 g to 12 000 tonnes (3).

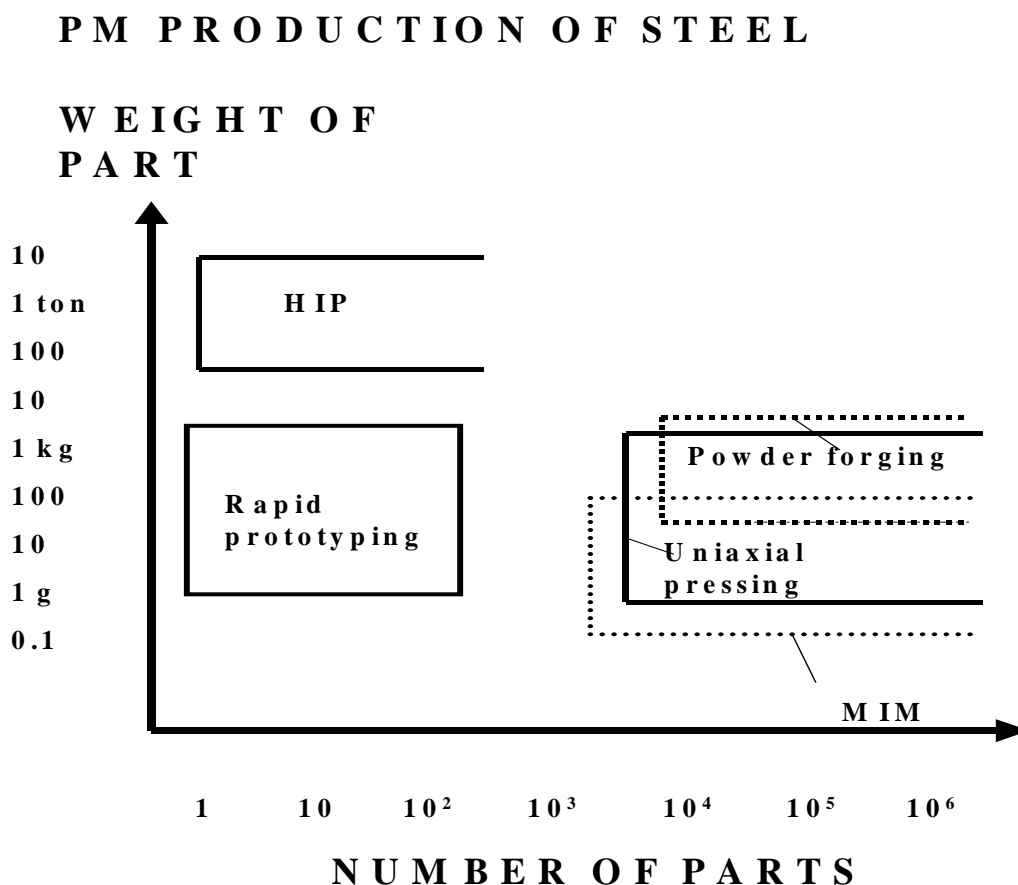


Figure 3. Technical – economical areas for different PM production methods of ferrous products.

Finally, semi - finished HSS products for example rods have been produced in the past by the process route: *melting + water atomization + encapsulation + hot extrusion*. There is still a minor production in Japan of HSS rods by hot extrusion of inert gas atomized powders.

Table 1 shows an estimate of the world production of ferrous products in general and of high speed steels + toll steel products using different powder metallurgical consolidation methods.

	Total ferrous PM Tonnes	PM HSS/tool steels Tonnes	Market share HSS/tool steels
HIP (billets + near net shape)	15 000	13 000	87%
Powder forging	30 000	-	-
Uniaxial pressing	700 000	3 000	0.4%
Powder injection moulding	2 500	25	1%

Table 1. World PM production 2004 of ferrous and HSS + tool steel products by different methods.

The above table shows that about 80% of the world PM production of HSS and tool steel are by hot isostatic pressing. As mentioned earlier, the by far dominating HSS product is valve seats inserts for engines to passenger cars.

The HSS and tool steel HIPed products consist of billets that normally are subsequently hot forged but also of a minor amount that are used as-HIPed. One important application example is as-HIPed high speed steel hollow bars for large broaches.

The total production volume of PM HSS and tool steel has not increased dramatically during several years. This is in spite the fact that very large investments have been done to modernise and increase capacity of existing production plants and the start up of a new plant at Böhler Edelstahl, Kapfenberg, Austria (4). Furthermore, many new high-performance HSS and tool steel grades have been introduced and very well received on the market.

There is a logical explanation for this contradictory situation of a rather slowly expanding market in spite of important process, materials and products developments in the same fields. The reason is that these developments have resulted in:

- large improvements of mechanical and functional properties and thus improved performance of established PM high speed steel grades
- developments of new high-alloyed and high performance new PM HSS grades designed for certain fields of application

This has in both cases given prolonged lifetime of the end products such as cutting tools as well as cold and hot forming tools. PM HSS is steadily used in new high demanding applications. The transition to PM high speed steel have in some important areas now come to nearly 100%, for example in gear cutting tools.

IMPORTANT DEVELOPMENTS OF PM HIGH SPEED STEEL

The R & D efforts have been very large and also in many aspects quite successful since the start, nearly 35 years ago, of industrial production of PM HSS and tool steels. This has resulted in considerably improved process technologies and numerous new alloys optimised for PM production. One very important objective has been to fully exploit the advantages inherent with powder metallurgical production of semi-finished products and net-shape or near-net-shape parts e.g. larger freedom in alloy design. One important advantage with PM production is that the lead-time from the first laboratory experiment to industrial production is very short compared with conventional production including casting and forging.

The following examples of development trends come primarily from the production of fully dense HSS and tool steels by hot isostatic pressing of nitrogen gas atomized powders followed by hot forming.

DECREASED CONTENT OF SLAG INCLUSIONS

Cast and forged high speed steels and tool steels contain two types of slag inclusions; endogenous and exogenous. The endogenous inclusions are primarily deoxidation products precipitated during the solidification of the steels. Exogenous slag inclusions are normally coarser than the endogenous ones and come from furnace slag, ceramic linings etc. that are entrapped in the liquid steel.

Fully dense PM steels, produced by HIP-ing of inert gas atomized powders, contain endogenous and exogenous slag inclusions, but also oxide inclusions deriving from surface oxides on the atomized particles.

The endogenous inclusions are for PM steels extremely small as a direct result of the very fast solidification process. It is possible to distinguish between the content of endogenous + exogenous inclusions and the content surface oxides by aid of a method originally developed by Grinder and Eriksson (5).

The surface oxides can have a negative effect on the mechanical properties of HSS products especially those that are used as HIP-ed. Large efforts have thus been made in order to decrease the content of these oxides by handling as-atomized powder in inert or reducing atmosphere. This has nowadays decreased the amount surface oxide to harmless levels.

It was shown in 1984 (6) that exogenous oxide inclusions were limiting the properties and performance of high speed steels and stainless steels produced by consolidation of nitrogen atomized powders by hot isostatic pressing or hot extrusion. It was found that the exogenous inclusions could have a direct negative effect on the strength, toughness and ductility of the fully dense PM high speed steels.

Figure 4. next page from (7) shows the relationship between the bend fracture strength and the apparent size of the crack initiation site.

In conventional HSS the initiation site is normally found at areas of carbide segregation. Accordingly, the exogenous slag inclusions are seldom a problem for these steels.

However, the contrary situations exist for the PM high speed steels. As they have a uniform, fine carbide structure it is often found that the cracks are initiated at exogenous inclusions. Major efforts have thus been made in order to decrease the amount and the maximum size of non-metallic inclusions in PM HSS and tool steels.

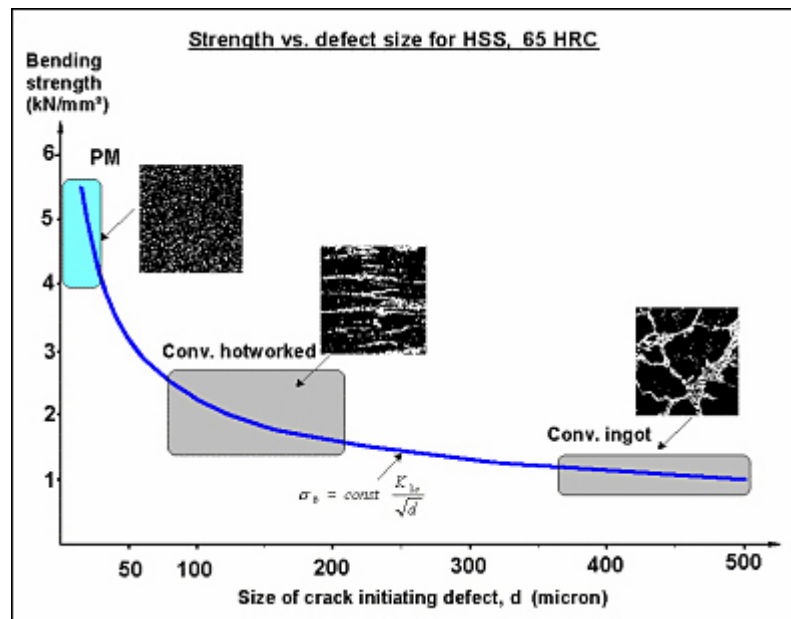


Fig. 4. Influence of the carbide structure on fracture initiation and bend fracture strength. HSS bar size.

In conventional HSS the initiation site is normally found at areas of carbide segregation. Accordingly, the exogenous slag inclusions are not a strength-limiting factor for these steels, but can often have a negative effect in other aspects.

Methods have been developed in order to enable inclusions to be separated in the tundish above the atomizing tower. The basic concept is to heat the steel melt in the tundish and to keep the steel melt in the tundish for sufficient time to enable the non-metallic inclusions to be separated from the melt before it is atomized. The steel melt is at the same time kept at a constant temperature suitable for the atomization process.

Three different methods are now used industrially for tundish heating. They are based on heating the melt with a plasma torch, induction heating and resistance heating of a slag layer covering the melt. These methods have found to be highly effective in decreasing the inclusion content in PM HSS and tool steels (8).

There is thus a direct relation between performance and functional properties of tools of PM HSS and the microstructure, cleanliness and inclusion contents of the high speed steels. This has motivated the main HSS producers to develop and invest in highly modern and advanced metallurgical process. PM production of high speed steels and tool steels are therefor nowadays high tech comparable to e.g. the PM production of super alloys for aero engines.

This improved microstructural control and decreased impurity and inclusion contents have resulted in continuous incremental improvement of established PM grades both regarding mechanical and functional properties (9) see e.g. figure 5 below.

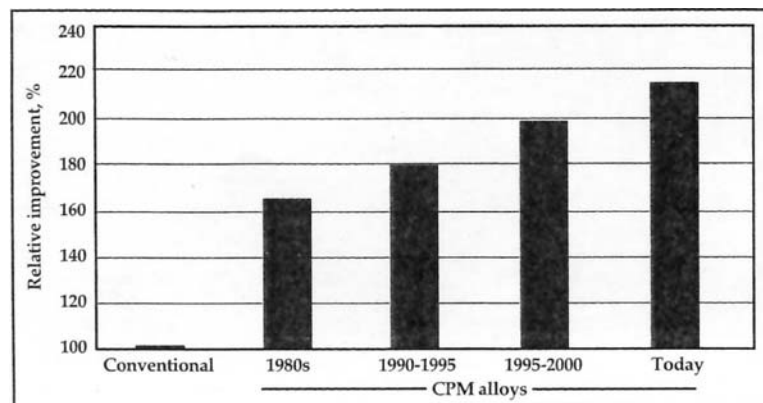


Fig. 5. Improved transverse bend fracture strength of Crucible CPM HSS steels.

RESULPHURIZED HSS

Sulphur forms sulphide inclusions, which have a negative influence on the mechanical and functional properties of conventional cast + forged HSS and tool steels. The situation is somewhat different in PM HSS and tool steels, as the sulphides precipitated are substantially smaller due to the high solidification rates during the atomization step. These small sulphides are evenly distributed throughout the steel and have less detrimental effect on e.g. hot workability. It has further been found that sulphur additions in the order of 0.10% to 0.15% to PM HSS and also tool steels, so called resulphurized grades, improve the machinability resulting in higher productivity and surface finish in the manufacture of gear cutting tools and other products (10).

NITROGEN ALLOYED PM HSS

Nitrogen alloyed PM high speed steels with 0.4 – 0.6 %N were developed in Japan by Kobe Steel Ltd already about 15 years ago (11-12). It has been reported that these nitrogen containing PM grades showed improved toughness and resistance to adhesive wear. See review of PM nitrogen alloyed HSS and tool steels (13).

New nitrogen alloyed PM tool steels with about 2 %N are now introduced on market with potential large applications in tools for powder pressing, blanking, forming and cold extrusion (14-15).

APPLICATION ORIENTED ALLOY DEVELOPMENT

High speed steel and tool steel products are when used exposed to a number of wearing and destructive mechanisms, including abrasive and adhesive wear, fatigue, thermal fatigue, impact and corrosion. The mechanisms prevailing vary between different applications and it is often difficult to determine which mechanism that is critical and dominating.

There is now a strong trend to develop PM alloys to meet specific demands in different important fields of applications in e.g. for wood cutting or powder pressing, see for example (10, 16). PM production of HSS and tool steels has in this respect several advantages compared with conventional production (casting + hot working) of HSS and tool steels.

Examples of such advantages are;

- rapid solidification gives no segregation and a fine, homogenous microstructure, which considerably increases the hot workability
- no carbide segregation and improved hot workability permits a higher volume percentage of carbides in the PM steel grades
- possibilities to vary the amount, the composition and also the size distribution of the carbides

Variation of the carbide size distribution can be obtained by changing the process parameters at the HIP-ing step. This makes it further possible to optimise the properties of the PM-steel for certain field of applications e.g.

- fine carbide size distribution for products exposed to high fatigue stresses (17)
- coarse distribution for products submitted to extensive abrasive wear (17, 18).

This development of new application oriented HSS and tool steels are based on the concept of *materials design* and latest theoretical instrument in the field of materials science.

Advanced thermodynamic calculation models such as Thermo-Calc are used to predict the microstructure of the new alloys, composition of the hard phases and matrix, hardening response etc. Different material models are also used to anticipate the material and functional properties of the steel in study.

This new working concept have effectively decreased the costs, work-load and time for development of new alloy systems and increased the competitiveness of PM high speed steel and tool steels versus primarily cemented carbides.

SURFACE STRUCTURE OF HSS TOOLS

It was mentioned above that coarse carbide and carbide segregates often initiate the fracture in service of tools made from conventionally cast and forged HSS and thus in some cases limit the performance. The critical and strength-limiting microstructural constituent for PM HSS tools was earlier in many cases exogenous slag inclusions.

The impurity and inclusion contents of PM HSS have during the last decade decreased to very low amounts due to investment in improved high-tech production facilities. This has gradually resulted in substantially increased importance of the surface quality of the PM high speed tools as internal defects such as carbide segregates or slag inclusions are no longer limiting the strength of tools manufactured from PM HSS.

The surface quality and thus also the performance of a tool is directly influenced of the different processing steps such as heat treatment, grinding, electro-discharge machining, nitriding, surface coating etc.

The surface quality is dependent on:

- surface roughness, surface defects such as scratches, burrs
- microstructural and chemical alterations close to the surface: phase transformation, heat affected zone, carburisation, decarburisation, oxidation, residual stresses, plastic deformation etc.

Figure 6 from (19) shows that the surface quality influences the bending strength for the PM HSS, in this case ASP 2023 but not for the conventional cast + forged HSS grade M2. It is also evident that the mechanical strength is about twice as high for the PM grade than for the M2 grade.

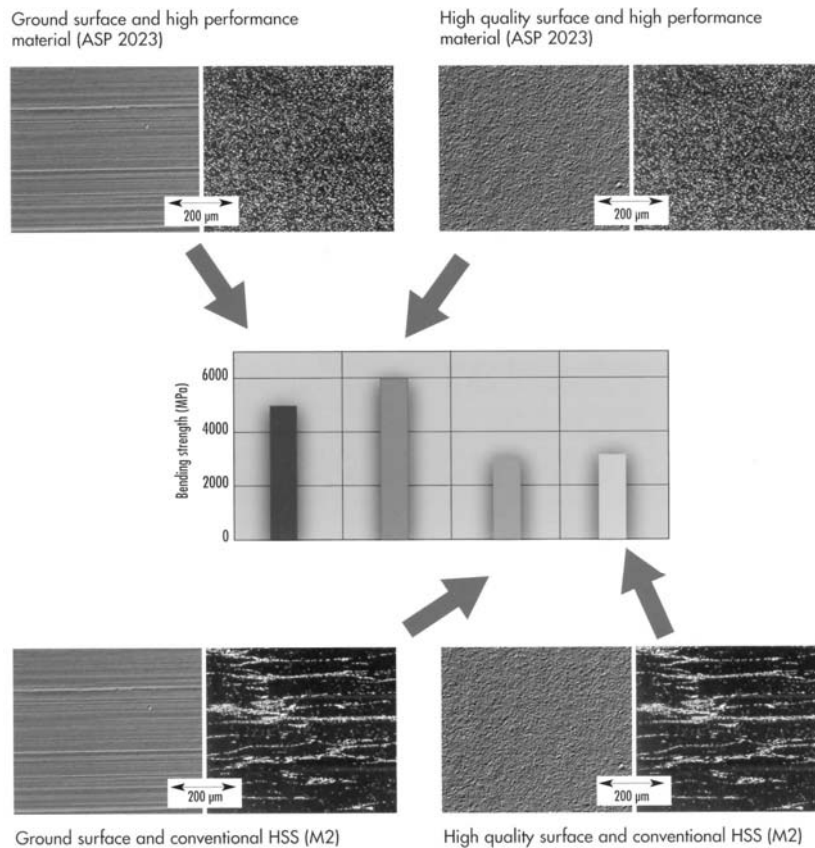


Fig. 6. Influence of surface quality on the bending strength of PM and cast + forged HSS.

NANOSTRUCTURAL HIGH SPEED STEEL AND TOOL STEELS

The development of nanosized powders and nanostructural materials has received a huge interest during the last years. It has been found that the mechanical and functional properties can be greatly improved by refining the grain size to the nanometer range.

There is also a considerable interest and potential in developing nano structural high-speed steels and tool steels. It has already been shown that prealloyed, nanocrystalline HSS powders can be synthesised by hydrometallurgical methods.

CONCLUSIONS

PM HSS and tool steels are now very well established on the international market with yearly sales value of some 100 million US dollars.

Several different PM production methods are used industrially enabling the manufacture from small net shape wear resistant parts with a weight in the gram range to semi finished billets weighting up to 12 tonnes.

The development of the PM high speed steels and tool steels is to a large extent the result of successful R & D efforts regarding the PM process technologies, optimisation of alloys and applications often in close co-operation with the end-users.

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