HIGH DENSITY PM COMPONENTS BY HIGH VELOCITY COMPACTION

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ABSTRACT

High Velocity Compaction (HVC) is a compaction method that enables high density and the possibility to make large P/M parts weighing up to more than ten pounds. The powder is compacted in less than 20 milliseconds by high-energy impact. Further densification is possible by adding multiple impacts as short as 300 milliseconds after each other.

High Velocity Compaction is a mass-production method that can expand the use of P/M beyond its present limitations.

High Velocity Compaction can be used in cases where components would require such high compaction force that the tonnage of conventional presses is a limitation.

This paper describes and discusses High Velocity Compaction. Properties of materials based on both pre-alloyed Astaloy powders and diffusion-alloyed grades at densities in the range of 7.4 -7.7 g/cm^3 are presented. This new manufacturing technology was recently introduced for P/M and examples are given of components that can be produced.

I. INTRODUCTION

The growth of the PM industry in recent years can to a very large extent be explained by the shaping ability of PM processes. This ability reduces, or completely eliminates, the need for machining of mass-produced structural parts. For the most demanding parts, the achievable material properties hold back further conversions from wrought steel to powder metallurgy. Further growth requires both improved static and dynamic performance.

Density influences the material properties considerably - the fatigue properties in particular.

In order to function properly, fatigue-loaded high-performing components need not only material performance, but also sufficient surface finish. The manufacturing methods for such components must therefore be capable of producing the required material properties and sufficient surface finish consistently in mass-production. New production methods for higher densities in combination with suitable materials and heat treatment open the way for many new applications. Recent developments such as Warm Compaction [1-4], Surface Densification [5-7], and High Velocity Compaction (HVC) [8-10] all contribute to creating PM parts with improved properties.

This paper covers the importance of density in respect to material properties for PM materials.

Examples of densities and mechanical properties achieved by various manufacturing methods are given. The paper briefly outlines the characteristics of HVC and highlights examples of achieved mechanical properties such as hardness, tensile strength and fatigue performance.

Materials and process combinations intended to match the requirements of high-performing components subjected to dynamic load are presented.

II. IMPORTANCE OF DENSITY

The importance of density on the properties of PM materials is paramount. See Figure 1. This study focuses on the potential growth achievable by improved mechanical properties and therefore only density levels above 7.0 g/cm3 are of interest. Numerous references cover the importance of density in powder metallurgy. [11-14]

The main reason why PM materials with the same structure as a corresponding wrought material show lower properties is the presence of pores that simply reduce the load-carrying area and increase the local stress in the material.

However, for most of the properties, strengthening the matrix with well-designed metallurgy/structure can compensate for the porosity-related drop in performance.

In the case of properties such as toughness and fatigue strength, pores can initiate cracks.

The size and shape of the largest pores are examples of factors that limit fatigue performance.

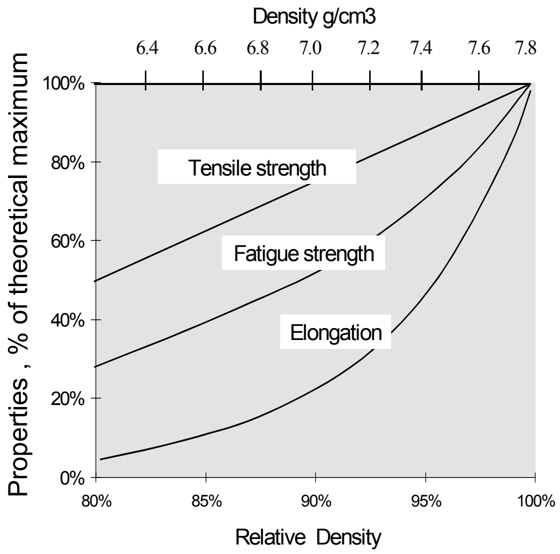


Figure 1. Principal materials properties relation to density for sintered ferrous steel

Materials-related factors that influence the fatigue performance are listed in Table 1.

Traditionally the trend towards high-fatigue performance focuses on minimizing the porosity and optimizing the structure of the matrix. Other significant factors for fatigue performance are residual stresses and impurities (size and shape). Residual stress can be both positive and negative. If residual stresses increase total stress, they reduce fatigue performance.

Table 1. Materials-related factors that influence fatigue performance

- Porosity
- Microstructure
- Residual stresses
- Impurities

Residual stresses achieved intentionally by surface rolling, shot-peening or case-hardening generally improve fatigue performance considerably. Increasing efforts are being made in component design and subsequent processing, which lead to material improvements locally in the most loaded areas.

Powder cleanliness with respect to impurities (i.e inclusions) in standard high-quality atomized powder materials is in most cases not considered a limiting factor, except for extreme applications subjected to very high load.

Besides the above, other component-related factors such as surface finish and notch sensitivity are of importance.

III. HIGH DENSITY TECHNOLOGY

The maximum achievable density has been steadily increased in recent years. See Figure 2. Initially, powders were made more compressible by modifying the shape of particles and by decreasing carbon, oxygen and impurity levels. The use of higher compaction pressures (600-1000MPa), more efficient lubricants (Kenolube) and Warm Compaction all lead to higher densities. Double Pressing and Powder Forging have also been developed in order to reach higher densities, despite the penalty of higher manufacturing costs. Improved alloying technique was developed to enable better mechanical properties without compromising on compressibility. Examples of such innovations are diffusion-bonded powders, which combine robust properties with minimum loss of compressibility, and pre-alloyed powders to which elements have been added to achieve high compressibility and a microstructure that result in high strength (i.e. Astaloy Mo).

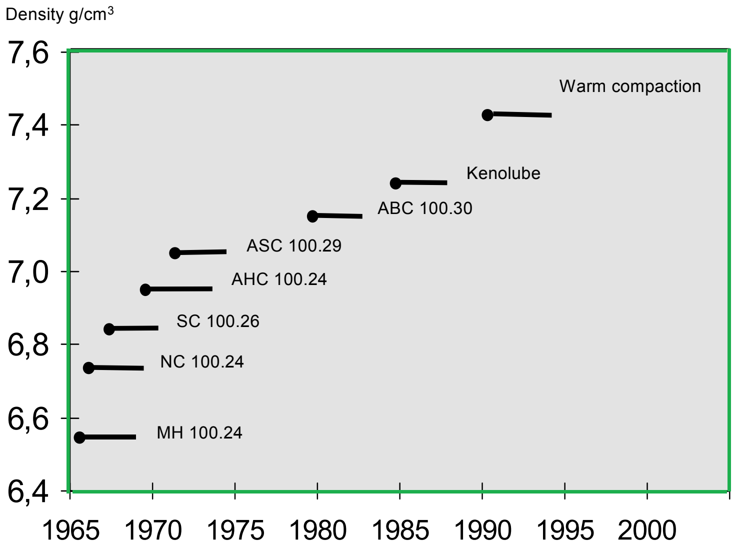


Figure 2. 30 years of density improvements in powder metallurgy

The performance of various compaction methods with respect to achievable density is indicated in Figure 3 and Table 2. Conventional compaction is by far the most established and frequently used manufacturing route in powder metallurgy. Double Compaction is also well established, but not so frequently used, mainly due to the fact that extra manufacturing steps mean higher production costs. Warm Compaction is increasingly used since it typically results in 0.2 g/cm^3 higher density than conventional compaction, but without any extra manufacturing steps. Powder Forging of sintered pre-forms results in almost full density and attractive fatigue properties. This is why Powder Forging, despite the high manufacturing costs caused by extra processing, has been successfully implemented for mass-production of automotive connecting rods.

The combination of selective Surface Densification with the leanest compaction routes presented in Figure 3 can be competitive, not least for gears, since the material can be processed to full density locally in the most loaded areas of the component.

The development of processes, and combinations of processes, that produce higher density, better surfaces and more delicate shapes at a lower cost is necessary to ensure growth of the PM industry.

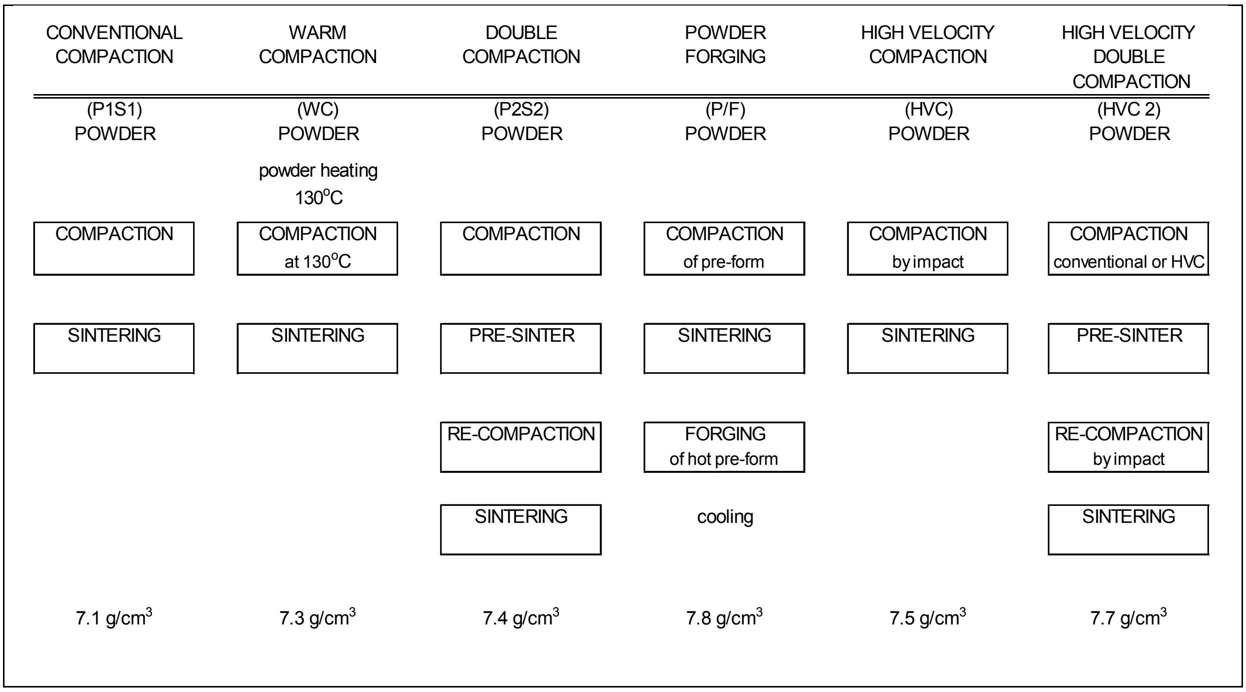


Figure 3. P/M manufacturing routes

A recently introduced manufacturing method that can offer improved properties is High Velocity Compaction (HVC). Various methods and equipment for compaction at high velocity have been investigated for almost half a century [15]. Compressed air, combustion of air–fuel mixtures, explosives, magnets and mechanical springs has been used to create kinetic energy for material forming and powder compaction. Many of these compaction methods were promising, and some still have potential. Some have suffered from macro- and micro-cracking of the compacted material caused by tensile wave reflections. This has even been considered a reason for the lack of large-scale commercialization of dynamic compaction.

The hydraulic impact machine concept is of particular interest for HVC because of its capability to mass-produce high-performance PM parts safely and reproducibly. By proper hydraulic control of the compaction process and adequate powder selection, microstructural defects due to uncontrolled axial expansion of the green body can be avoided.

IV. HIGH VELOCITY COMPACTION

High Velocity Compaction (HVC) is a powder compaction method that has many similarities to conventional compaction of PM parts. The most striking differences are that the stage of compaction can be 500-1000 times faster and that the ram speed of a HVC impact machine can be in the range of 2-30 m/s. Densification in HVC is achieved by intensive shockwaves created by a hydraulically-operated hammer, which transfers the compaction energy through the compaction tool to the powder. The mass of the hammer and its velocity at the moment of impact determine the compaction energy and the degree of densification. A schematic illustration of the process equipment and a graph illustrating the shock waves are shown in Figure 4.

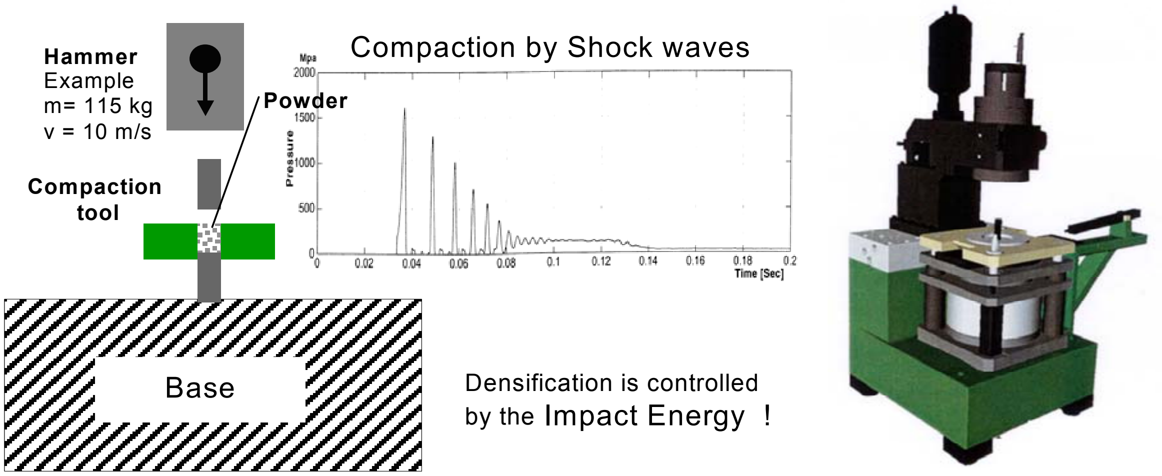


Figure 4. Basic mechanism of HVC and Hydropulsor HYP35–4 impact machine (4 kJ maximum compaction energy; 2 950 ft lb) with automatic tool adapter

An interesting feature of HVC is the possibility to perform multiple impacts. In conventional compaction, the density does not increase significantly if the pressing sequence is repeated directly after the initial compaction. However, using HVC density can be increased impact by impact. An advantage of increased densification following multiple impacts, is that it is possible to compact large parts with moderately-sized equipment. Component production by HVC consists of the same processing steps as conventional compaction and the compaction tool design is similar to conventional compaction tools. Good production economy requires sufficient tool life and it is therefore reassuring that the endurance limit of HVC tools has been verified to exceed a minimum of 100,000 cycles in a full-scale compaction test [10].

The mechanical properties of P/M materials increase in proportion to the increased density achieved by HVC. A typical density increase of 0.3 g/cm³ has been recorded for high velocity compacted materials based on D.AE and Astaloy CrM™, compared to density levels representative of conventional compaction. As a result of the higher density, 20–25% higher tensile and yield strengths have been obtained.

Radial springback of a compact is generally lower for HVC than for conventional compaction. Lower springback generally leads to the advantage of lower forces being required to eject a part from the die after compaction. HVC has the capability to produce parts with not only high densities, but also very consistent densities. Compaction tests on prototype gears have shown density variations of less than 0.01 g/cm³. Approximate densities achievable with HVC combined with die wall lubrication (DWL), warm compaction (WC), and double press, double sintering (P2S2) are presented in Table 2.

Table 2. Approximate max densities achieved by HVC

Process	Density (g/cm³)
HVC	7.4
HVC+DWL	7.6
HVC+WC+DWL	7.7
HVC (P2S2)	7.8

Potential applications for HVC exist both in the automotive industry and in other areas where P/M has not yet been established. Examples of potential applications are: valve seats, valve guides, main bearing caps, hubs, gears [8,10], flanges, connecting rods, cam lobes, bushings and bearing races. See Figure 5.

Figure 5. Left: Gear for High Velocity Compaction - courtesy of Cloyes Gears & Products Inc., USA
Right: Gerotor for High Velocity Compaction - courtesy of Hawk Precision Components, USA

Recent R&D in the area of High Velocity Compaction [9] concludes that the major advantages HVC can offer are: high density, the capability to compact very large parts, and the possibility to produce high numbers of parts in a short time.

V. COMPARISON OF PROCESSING COSTS

Processes that can offer improved material properties with no or moderate increase in manufacturing costs are of particular interest to the automotive industry, since they can expand the use of P/M applications in cars and reduce the total cost for the end user.

The approximate relative processing cost for various P/M processes, using conventional single pressing as a reference, is presented in Figure 6. Production methods that only involve a few processing steps, have a high production capacity and require a minimum of investment for the equipment are of special interest. This applies particularly if net shape or near net shape parts can be produced as a result of good tolerances and surface finish.

A good cost/performance ratio explains why the conventional compaction method is the most established and most frequently used. This also explains the recent success of warm compaction, which is increasingly used and has now spread worldwide.

Process:
P1S1
Conventional compaction
WC
Warm Compaction @150^{0}C
P2S2
Double Press Double Sintered
PF
Powder Forging
HVC
High Velocity Compaction (P1S1)
HVC 2
High Velocity Compaction (P2 S2)

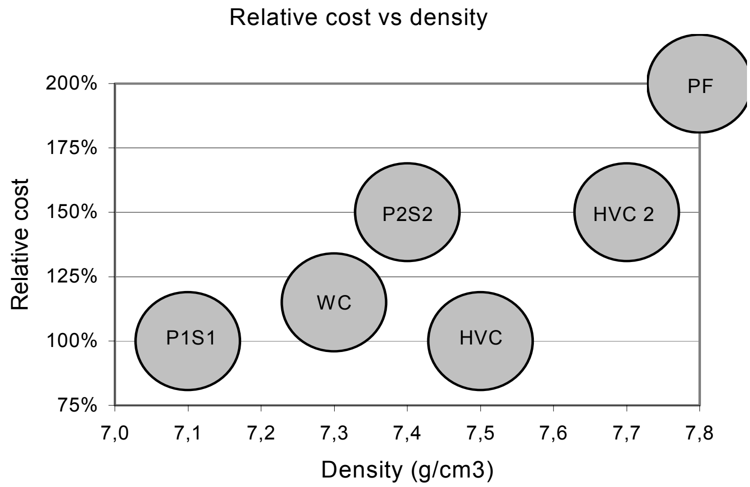


Figure 6. Relative processing costs

For many high-performance applications HVC single compaction is the most attractive from a cost/performance point of view. Conventional double compaction has been established for many years, but is limited due to high costs. HVC double compaction has a real advantage compared to the conventional double pressing route because of a much higher achievable density and the better material properties that result. Powder Forging is a double compaction step process, in which the final hot compaction step fully densifies the material. Because of the high temperature, the surface finish and tool economy are inferior compared to the other mentioned processes.

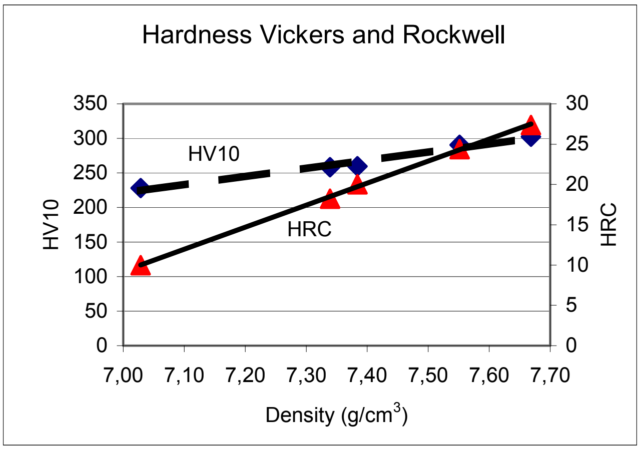
VI. PROPERTIES OF HIGH VELOCITY COMPACTED MATERIALS

The static mechanical strength of various materials obtained from test bars compacted by HVC has been used in order to verify the performance of the material after final processing. Material properties at density levels of 7.5 – 7.7 g/cm^3 obtained by HVC are presented and compared with the properties achieved by other compaction methods that lead to densities ranging from 7-7.4 g/cm^3. Figure 3 indicates representative density levels for the various compaction methods used. The highest density, the 7.7 g/cm^3 level, was reached via the HVC P2S2 route. This procedure begin with conventional compaction to approximately 7.2 g/cm^3 followed by pre-sintering and final High Velocity Compaction to target density. For the next highest density, the 7.5 g/cm^3 level, the HVC P1S1 route with die wall lubrication was used. Sintering has been performed using a laboratory mesh-belt furnace in a nitrogen-based protective atmosphere at 1120^{o}C (2050^{o}F) for 30 minutes. The cooling rate is 1^{o}C/s (2^{o}F/s). Properties originate from finally processed test specimens produced without any machining. More information about properties of high-performance materials including details on test procedures has been reported recently. [16]

Two materials, Astaloy Mo +2%Ni +0.6%C and Astaloy CrM ™ +0.4%C, were used for determination of the properties in the as-sintered condition. Both materials are based on fully pre-alloyed water-atomized iron powders. Astaloy Mo is alloyed with 1.5% molybdenum, Astaloy CrM ™ with 3% chromium and 0.5 % molybdenum. After sintering the Astaloy Mo based material has a metallographic structure containing 75% Bainite, 20% Martensite and 5% Austenite. Metallography on Astaloy CrM ™ showed 70-75% Bainite and 25-30% Martensite.

Astaloy Mo +2%Ni +0.6%C:

Hardness and tensile properties increase proportionally with increased density up to the maximum density, 7.7 g/cm^3. Astaloy Mo +2%Ni +0.6%C reaches a maximum hardness of over 300 HV_{10} or 27 HRC at a density of 7.68 g/cm^3. See Figure 7.



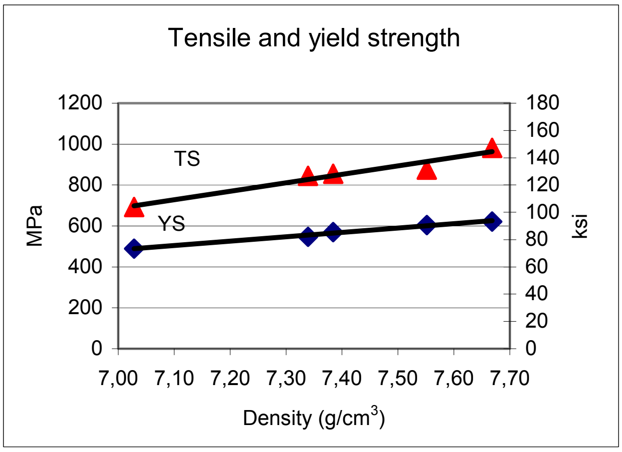
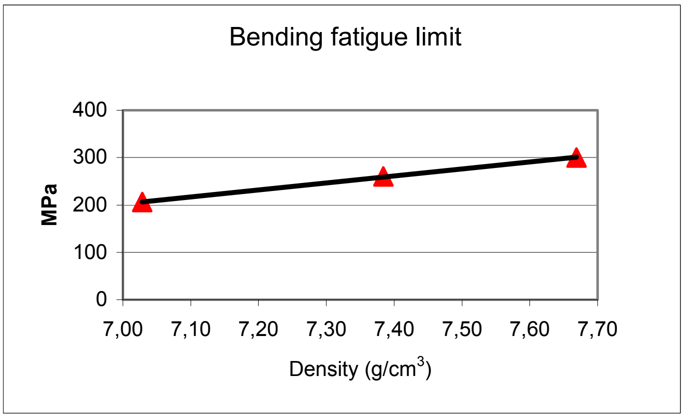


Figure 7. Mechanical properties of AstaloyMo +2%Ni +0.6%C sintered at 1120°C (2050°F) in 90%N_2/10%H_2

A tensile strength of 980 MPa and a yield strength of 620 MPa was recorded at this density. The corresponding elongation is 4.7%. This is more than three times the elongation value recorded at the density of 7.0 g/cm^3 achieved by conventional compaction.
In Figure 8 the bending fatigue life for Astaloy Mo +2%Ni +0.6%C at three density levels is shown. At 7.7 g/cm^3 run-out was achieved at 300 MPa, which is also a great improvement compared with lower densities.

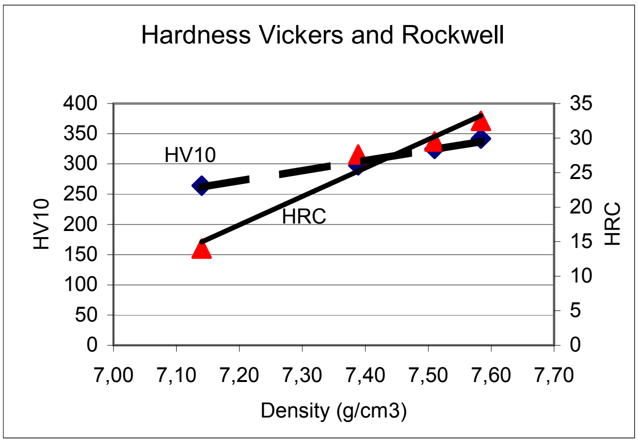


Four point bending test:
50% fatigue limit
R= -1
Frequency 25 Hz
Run out @ 2 000,000 cycles
Test bar: ISO std 3928 as pressed, sintered and tempered (no machining)

Figure 7. Bending fatigue limit of AstaloyMo +2%Ni +0.6%C sintered at 1120°C (2050°F) in 90%N_2/10%H_2

Astaloy CrM+0.4%C:

Astaloy CrM +0.4%C also shows considerably improved properties at high density. At the highest density, which is close to 7.6 g/cm^3, a hardness of 340 HV_{10} or 33 HRC was observed.
See Figure 9. The tensile strength at this density level is 1150 MPa and the yield strength 800 MPa.



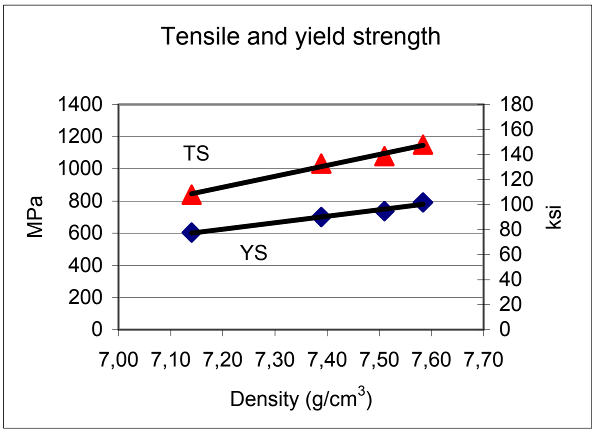


Figure 9. Mechanical properties of Astaloy CrM +0.4%C sintered at 1120°C (2050°F) in 90%N_2/10%H_2

Astaloy CrM + 0.4%C and D.DH1 +0.6%C   as-sinter-hardened

Materials properties can be improved significantly with only a moderate cost increase by using sinter – hardening [17,18]. Previous studies [8] have shown that gears produced by HVC and sinter-hardening can match the properties of gears made from wrought materials. Therefore, a part of this work was devoted to determining the mechanical properties of two materials suitable for sinter-hardening: Astaloy CrM +0.4%C and D.DH1 +0.6%C.
D.DH-1 is a water-atomized iron powder containing 1.5% molybdenum (pre-alloyed) and 2% copper (diffusion-bonded).

Table 3. Properties of sinter-hardened materials at 7.5 g/cm³

	Tensile strength		Yield strength		Hardness	
	(MPa)	(ksi)	(MPa)	(ksi)	HV_{10}	HRC
AstaloyCrM +0.4%C	1370	191	1230	171	480	44
D.DH1 +0.6%C	1500	208	1190	166	475	46

Sintering:1120°C 30min 90%N_2/10%H_2 cooling 5°C/s (9°F/s) + tempering 200 °C – air

Astaloy CrM +0.4%C reaches a maximum hardness of 480 HV_{10} or 44 HRC at a density of 7.5 g/cm³. The tensile strength is 1370 MPa and the yield strength 1230 MPa. See Table 3.
For D.DH1 +0.6%C at the same density, the corresponding hardness is 46 HRC or 475 HV_{10}. The tensile strength is 1500 MPa and the yield strength 1190 MPa.
At the density level 7.58 g/cm³, hardness is 50 HRC for the D.DH1-based material. With even higher densities, optimized carbon content and increased cooling rates during sinter-hardening, hardness values above HRC 60 can be expected.

Astaloy Mo + 0.2%C as-case-hardened:

Properties suitable for high performance gears can be achieved by using low-carbon materials, which are compacted to high density and then case-hardened after sintering. Case-hardening increases surface carbon content and the subsequent quenching leads to a hard, fully martensitic surface layer and compressive stresses. A consequence of the case-hardening is improved performance with respect to root bending fatigue as well as flank wear. In Table 4, properties in the as-case-hardened condition are presented. The data originates from pressed and sintered (HVC - P2S2) test bars that have been case-hardened. Carburizing was performed at 920°C for 100 min at a carbon potential of 0.8%C followed by quenching in oil and tempering at 180°C for 60 min in air. The case depth is 0.5 mm. A hardness profile and micrographs are presented in Figure 10.

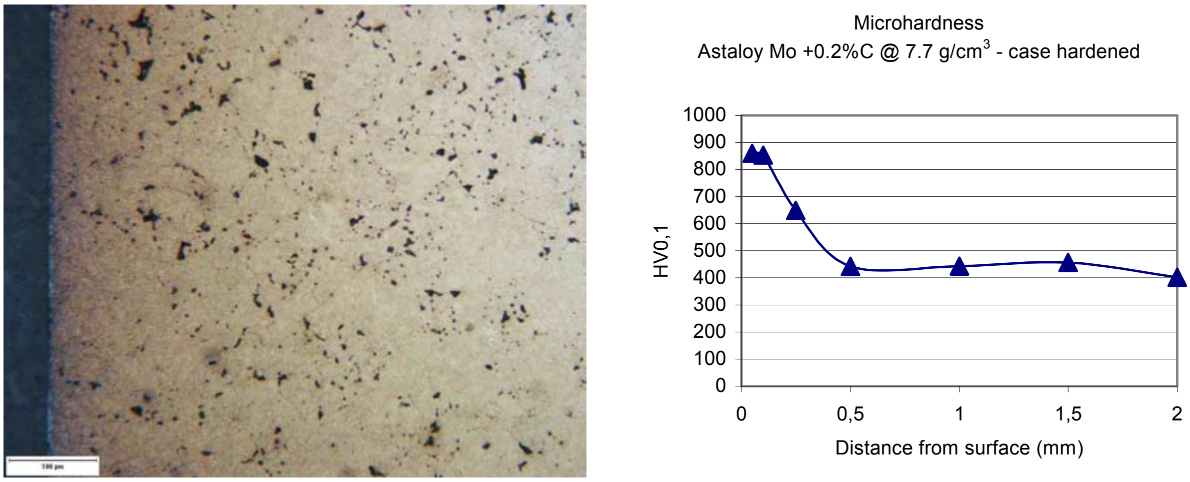


Figure 10. Micrograph and hardness profile for case-hardened test bar. Astaloy Mo+0.2%C @ 7.7g/cm3

A surface hardness of 57 HRC or 790 HV_{10} was observed at the maximum density, 7.7g/cm^3. The most striking effect can be seen in the bending fatigue limit that rises to at least 550 MPa. The level of bending fatigue performance achieved due to the high density and the case-hardening is of great interest since this property can be related to the root bending fatigue performance of a gear.

Table 4. Properties of case-hardened Astaloy Mo + 0.2%C

	SD	Hardness		Tensile strength		Yield strength		Bending fatigue limit	
	(g/cm^3)	HV_{10}	HRC	(MPa)	(ksi)	(MPa)	(ksi)	(MPa)	(ksi)
HVC	7,54	730	54	960	134	720	100	Not tested	
HVC Double pressed	7,70	790	57	1040	145	805	112	+550*	76

Sintering:1120^{o}C 30min 90%N_2/10%H_2; Case-hardened and tempered
* Comment: Upper limit of the fatigue test equipment was reached

The relevance of tensile and yield strength values generated from case-hardened test bars can be questioned since they are not useful in component design. However, they indicate the degree of strength increase compared to an as-sintered material with the same or similar matrix. A tensile strength in the order of 1000 MPa was observed for the case-hardened samples.

VII. DISCUSSION

Development of new high-density methods expands the potential of powder metallurgy by improved material performance. High Velocity Compacted PM materials can reach very high ultimate tensile strength in combination with high ductility. In the experiments described in this paper, tensile strength exceeding 1000 MPa and an elongation of approximately 5% have been recorded for a FN0206 material. The combination of high density and sinter-hardening has proven to offer significant improvement in mechanical properties. Faster cooling during sinter-hardening, preferably faster than 5^{o}C/s (10^{o}F/s) for production furnaces, would be advantageous since more of the potential of the high-density materials could then be utilized. Case-hardened high-density materials are very attractive for high-performing gears since the hardness and compressive stresses have a potential to significantly reduce flank wear and improve root bending fatigue performance to levels that can meet the requirements for proper function.

VIII. CONCLUSIONS

As-sintered material properties of high velocity compacted pre-alloyed materials at densities ranging from 7.5 g/cm^3 to 7.7 g/cm^3 have been determined. These have been compared to the corresponding properties at density levels representative for conventional compaction, warm compaction and the double press double sinter route.

It has been concluded that the increased density levels achieved with HVC result in proportionally higher values for hardness as well as tensile and yield strengths.

Properties of sinter-hardened materials, based on Astaloy CrM and D.DH1, have been determined at density levels exceeding 7.5 g/cm^3 achieved by HVC.

The combination of high density achieved by HVC and sinter-hardening makes it possible to produce stronger materials and use less processing compared to other established manufacturing processes.

Properties of as-case-hardened Astaloy Mo +0.2%C at density levels exceeding 7.5 g/cm^3 achieved by HVC have been determined.

The properties of this material, including fatigue performance, can match the requirements for high-performance gears.

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