Chromium Alloyed PM Steels – Cost-Effective High Performance Material Solutions

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Abstract

Cost-effective material solutions with high performance will be required to continue to grow the PM industry and expand the use of PM into more demanding applications. Chromium alloyed PM steels combine excellent mechanical properties with good dimensional stability, as well as stable alloying costs when compared to traditional Mo/Ni alloyed material. Sustainability is also becoming a more important factor in the selection of material and processing conditions. Utilizing the PM process with chromium materials is proven to be a sustainable solution with less influence on the environment. The combination with the sinter-hardening process makes chromium material even more competitive. By increasing the conventional sintering temperature of 1120 ºC to a higher temperature of 1250 ºC, the properties of chromium materials can be developed further. In this study, some chromium alloyed materials will be presented and the properties achieved after conventional sintering at both 1120 ºC and 1250 ºC are discussed. The environmental impact of chromium material and high performance applications which utilize chromium alloyed PM steels will also be described.

1. Introduction

For some time the PM industry has faced the challenge of continuously improving the mechanical properties for structural PM parts. The demand for cost-effective material with high mechanical performance level has grown significantly in recent years, especially for automotive applications. Chromium as an alloying element has been used in conventional steels for a long time due to its high hardenability, relatively low cost and recyclability [1-2]. The utilization of Cr in PM steel in the past was limited due to the oxidation sensitivity of Cr during sintering. Traditionally, molybdenum and nickel are commonly used as alloying elements in low-alloyed PM steel to enhance the hardenability and strength of structural PM components. However, in recent years the dramatic volatility of prices has put considerable pressure on budgets. This has led to a reduction in profitability across the entire value chain, making PM technology less competitive than manufacturing processes such as forging and casting. Figure 1 shows the changes in prices for metal elements when compared to Cr between 2005 and 2017.

Due to these changes there is a growing interest in utilizing more cost-effective alloy systems to enhance mechanical properties. Over recent years, a number of water-atomized and pre-alloyed Cr materials have been developed for the market. With continuous improvements in powder production processes and sintering conditions of PM components, these pre-alloyed Cr materials can all be sintered using conventional belt furnace sintering conditions at 1120 °C in nitrogen and hydrogen atmosphere, with oxygen at a partial pressure lower than $5*10^{-18}$atm [3].

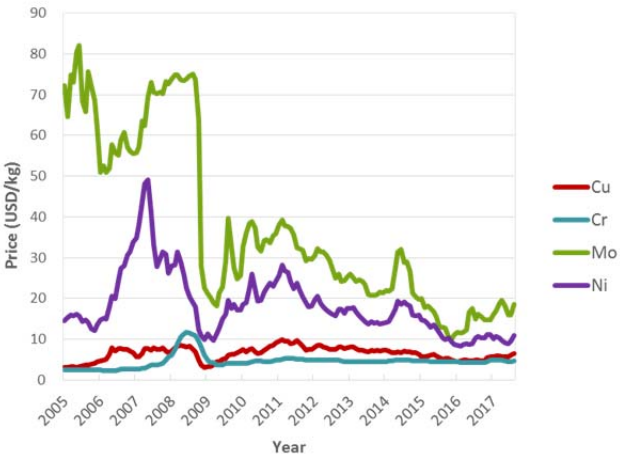


Figure 1. Metal element price development during 2005~2017 (source: London Metal Exchange).

Sinter hardening is a cost-effective process to obtain high hardness and high strength PM parts without the subsequent heat treatment process. High temperature sintering can facilitate the sintering of PM materials, resulting in improved density and mechanical properties. The benefits of utilizing Cr-alloyed powder grades in sinter hardening and high temperature sintering have been reported in several earlier studies [4-7]. There is now a growing awareness of sustainability when selecting raw material and considering manufacturing technology, because these impact on the environment by consuming resources such as energy. Therefore, it is necessary to evaluate and select both material and manufacturing technologies with the least influence on the environment [8].

2. LCA analysis between components manufactured by PM technology vs. conventional wrought steel technology

A major issue for industries to consider in modern society is the environment and the impact of their activities upon the ecological system for existing and future generations. PM has two major environmental advantages, and these are high material utilization and low energy consumption. The LCA (Life Cycle Assessment) is a systematic approach that can be used to evaluate the environmental influence of PM technology and conventional wrought steel technology [9].

2.1 Injection yoke component LCA analysis

A comparative LCA study was carried out on the injection yoke shown in Figure 2.

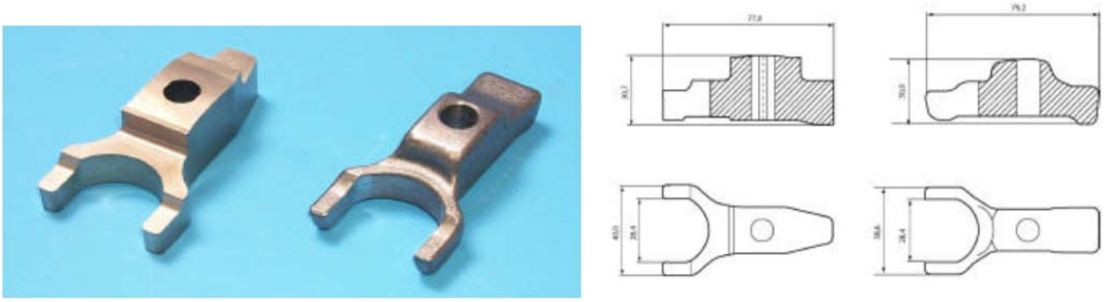


Figure 2. Injection yoke. PM yoke to the left and forged steel yoke to the right.

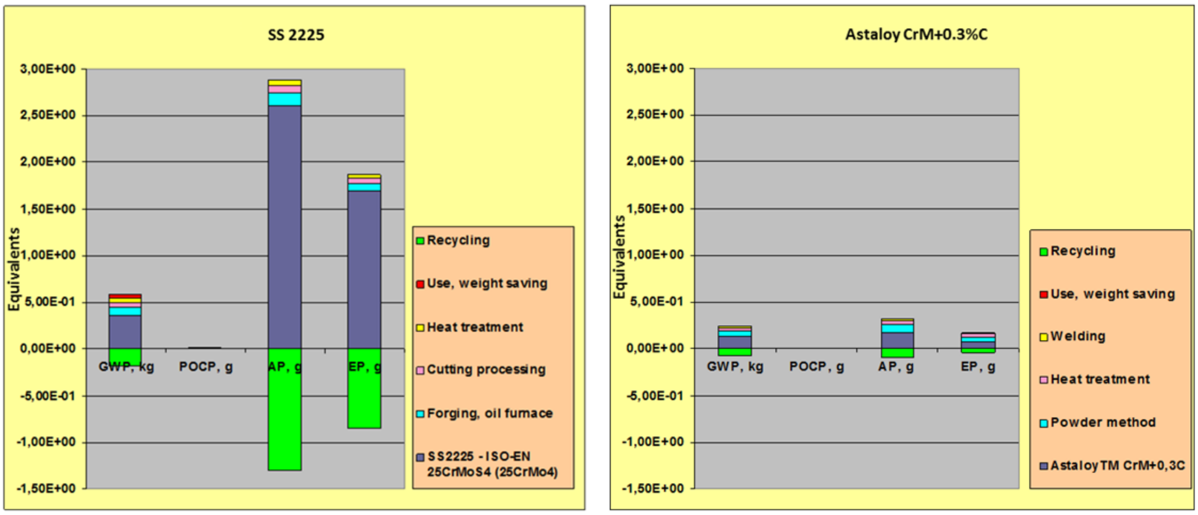
The main objective of this study was to compare the environmental impact when producing a component by wrought steel technology and by PM technology. The environmental impact is calculated and expressed using Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP) and Eutrophication Potential (EP). Another objective was to compare two different PM materials made from steel scrap such as Astaloy CrM and Distaloy AE. Astaloy CrM is a pre-alloyed material containing 3.0 wt% Cr and 0.5 wt% Mo. Distaloy AE is a diffusion alloyed material containing 4.0 %Ni, 1.5 %Cu and 0.5 % Mo. Both materials are suitable for high strength applications and input data for their comparison is provided in Table 1.

Table 1. Input data for comparison between PM and wrought steel for injection yoke component.

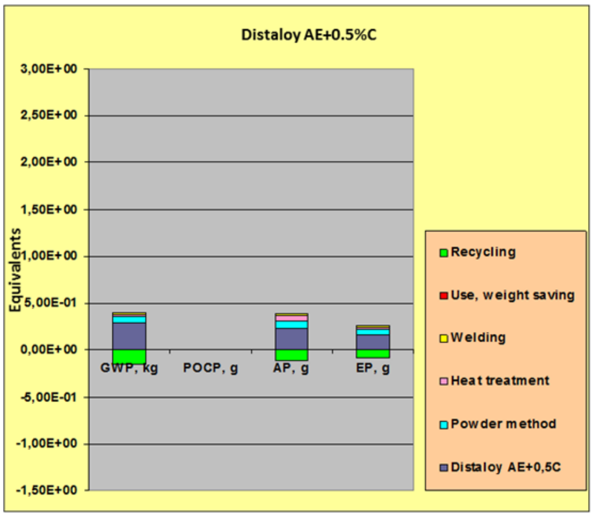
Material	**Weight of final component, g**	**Material utilization, %**	**Processing**
SS2225 ISO-EN 25CrMoS4	194	68	Forging, Machining, Heat treatment
Astaloy CrM+0.3%C	196	97	Compaction, Sinter hardening
Distaloy AE+0.5%C	196	97	Compaction, Sintering, Heat treatment

2.2 LCA analysis result

The result of the LCA analysis is shown in Figure 3. As can be seen, compared to conventional wrought steel technology, the environmental impact of PM technology is substantially lower in terms of depletion of natural resources, acidification and eutrophication because of the lower energy consumption. The comparison between the two PM materials shows that Astaloy CrM, a material containing chromium has even less environmental impact than Distaloy AE, a material containing Ni, Cu and Mo. The higher figure for Distaloy AE is primarily due to the high Ni content.



a) SS2225 b) Astaloy CrM+0.3%C



c) Distaloy AE+0.5%C

Figure 3. LCA result of a) SS 2225, b) Astaloy CrM+0.3%C, and c) Distaloy AE+0.5%C.

The LCA analysis demonstrates the environmental advantages of PM technology over the conventional wrought steel technology when producing high performance components. The results also show the advantage of using Cr alloyed PM material instead of high Ni content material. The properties achieved by two Cr alloyed powders are presented later in this paper. By utilizing different processing routes these two PM materials exhibit excellent properties and are suitable for new applications with high demands.

3. Experimental procedure

Two commercial water-atomized powders, Astaloy CrA pre-alloyed with 1.8 wt% Cr and Astaloy CrM pre-alloyed with 3 wt% Cr and 0.5 wt% Mo were evaluated in this investigation. Test mixes were prepared by adding different amounts (0.5-0.8 wt%) of graphite (C-UF from Kropfmühl) and lubricant (0.6 wt% Lube E) to the base powders and mixed using a laboratory mixer. Copper powder (-200 mesh) and nickel powder (Inco-123) were also used as alloying additives in some of the mixes. Chemical composition and material codes are shown in Table 2.

Table 2. Chemical composition of the powder mixes used in this investigation.

Material code	**Base powder**	**Cr (wt%)**	**Cu* (wt%)**	**Ni* (wt%)**	**Mo (wt%)**	**Graphite (wt%)**
CrM+0.5C	Astaloy CrM	3	-	-	0.5	0.5
CrA+0.8C	Astaloy CrA	1.8	-	-	-	0.8
CrA+1Cu+0.6C	Astaloy CrA	1.8	1	-	-	0.6
CrA+2Ni+0.6C	Astaloy CrA	1.8	-	2	-	0.6

*(Admixed)

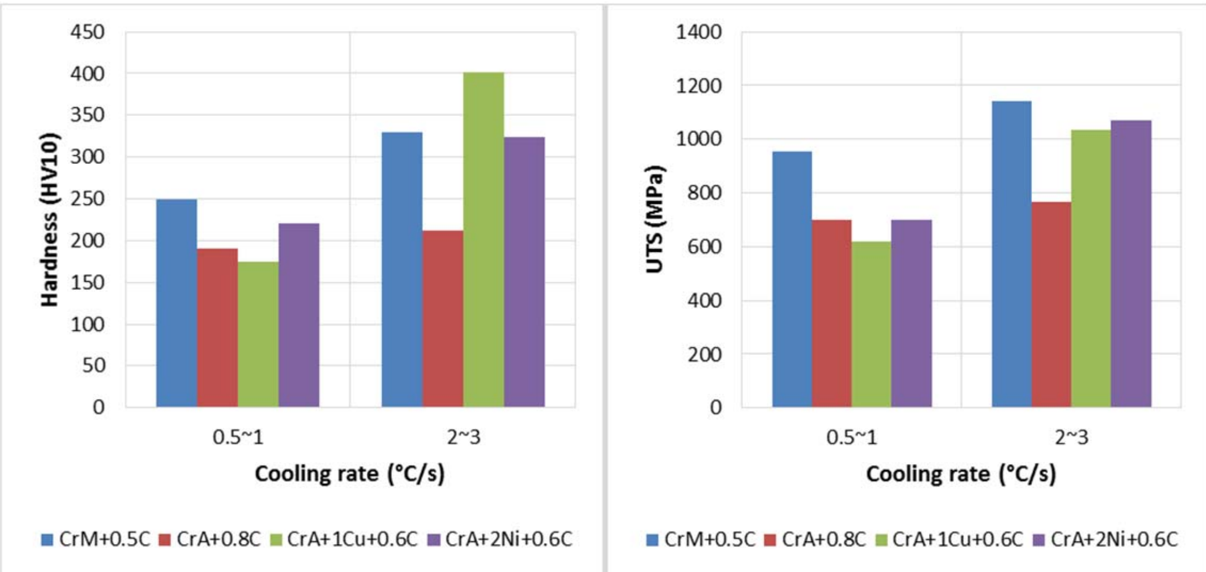
Standard test specimens for tensile testing (ISO 2740) and impact testing (ISO 5754) were compacted to a green density of 7.0 g/cm^3 with a hydraulic press. Sintering was carried out in a newly designed sintering furnace with the ability to achieve a maximum sintering temperature of 1400 °C and equipped with a fast cooling system able to achieve cooling rates of up to 8 °C/s. The furnace was driven by a pushing system in the dewaxing zone, a rolling system in the sintering zone and a separate cooling zone. This means the cooling time for the sinter hardening can be controlled separately by the driving system.

In this investigation, two different cooling rates of 0.5~1 ºC/s and 2~3 ºC/s were used. The conventional sintering temperature used was 1120 ºC and for high temperature sintering it was 1250 ºC. The total sintering time was 30 minutes. The protection atmosphere was 90/10 N_2/H_2 mixed gas. After sinter hardening, the specimens were tempered at 200 ºC for 60 minutes in air for stress relief. Mechanical properties were evaluated using Vickers hardness measurements (ISO 6892-1), a tensile test (ISO 6892-1) and a Charpy impact test (MPIF40).

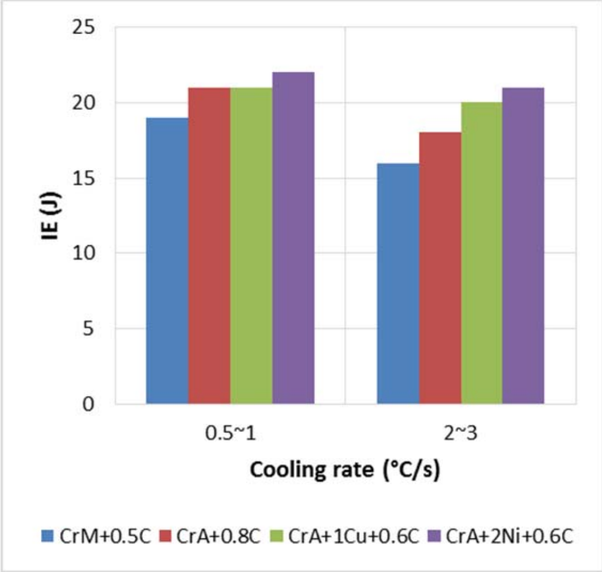
4. Result and Discussion

4.1 Conventional sintering and sinter hardening

The oxygen content of all the materials was around 0.05~0.08% and the carbon loss during sintering was approximately 0.05 %. Mechanical properties after conventional sintering with different cooling rates are shown in Figure 4. Astaloy CrM obtained the highest ultimate tensile strength (UTS) of 953 MPa and a hardness of 250 HV10, with an impact energy of 19 J using conventional sintering conditions. The three Astaloy CrA materials have similar mechanical properties at a slow cooling rate. Nevertheless, Astaloy CrA with Ni addition exhibited a good combination of strength and ductility. By utilizing sinter hardening, the mechanical properties of all materials improved. Tensile strength increased from 10~20 % for both Astaloy CrM and Astaloy CrA compared to conventional sintering, and from 953 MPa to 1144 MPa for Astaloy CrM and 700 MPa to 767 MPa for Astaloy CrA. Astaloy CrA material responded very well to the sinter-hardening process with the addition of Cu and Ni. The hardness and tensile strength were significantly improved. Astaloy CrA with Cu reached a tensile strength of 1034 MPa, an improvement of more than 60 % while Astaloy CrA with Ni achieved a tensile strength of 1069 MPa, with an increase of up to 50 % when compared to conventional sintering. The hardness level obtained by both materials is in the range of 300~400 HV10. The impact energy is very comparable at both conditions for all the materials, and somewhat higher at a slow cooling rate.



a) Hardness. b) Ultimate tensile strength.



c) Impact energy

Figure 4. Mechanical properties of different material sintered at 1120 °C with different cooling rates.

The results above show excellent static properties for Cr-alloyed materials, especially using sinter-hardening conditions. In a study by Engström and others, the dynamic performance of Astaloy CrM and Astaloy CrA with Cu and Ni additions was investigated [8], as shown in Figure 5. For the plain Astaloy CrM material a plane bending fatigue strength of 363 MPa was achieved. With warm compaction Astaloy CrA+2%Ni exhibits the highest bending fatigue strength of 379 MPa at 50 % survival. When creating a higher carbon content at the surface, an even higher fatigue strength of around 447 MPa can be achieved.

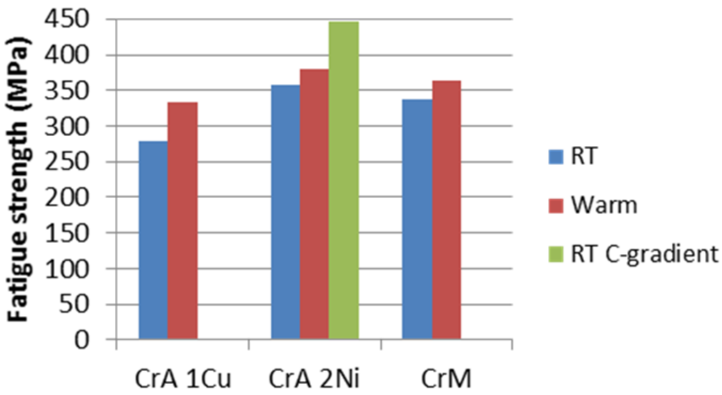


Figure 5. Plane bending fatigue strength of conventional, warm-compacted Astaloy CrA with Cu, Ni and Astaloy CrM using conventional sinter-hardening conditions [8].

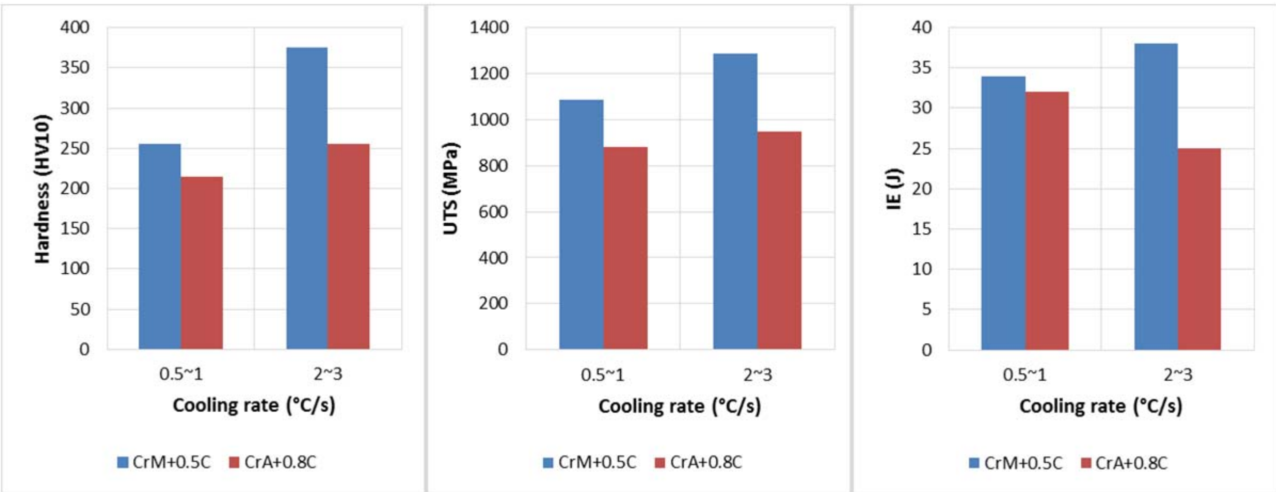
4.2 High temperature sintering and sinter hardening

Higher temperatures are beneficial for the sintering of PM materials. As the sintering temperature increases, the diffusion and sintering activity is also increased, resulting in improved sintering necks, more rounded pores and an increase in density. These factors not only improve the strength, but they also increase the mechanical properties and ductility due to the improvement in pore structures.

For chromium alloyed materials, more efficient oxide reduction during high temperature sintering may also contribute, even though the remaining oxides after conventional sintering should have no significant effect on the properties.

Mechanical properties achieved after high temperature sintering with different cooling rates are shown in Figure 6. The oxygen content of both materials is around 0.02 % while the carbon loss during sintering at 1250 ºC is approximately 0.1 %. As expected, the mechanical properties of both Astaloy CrM and Astaloy CrA are enhanced when sintered at a higher sintering temperature. High temperature sintering of Astaloy CrM gives a good combination of strength and toughness at both cooling rates. At a cooling rate of 0.5~1 ºC/s, ultimate a tensile strength of over 1000 MPa is obtained with an impact energy of 34 J. If combined with a higher cooling rate, the hardness, strength and toughness of Astaloy CrM are further improved. In addition, a tensile strength of over 1200 MPa is achieved, together with a hardness of around 375 HV10 and an impact energy of 38 J.

By raising the cooling rate from 0.5~1 °C/s to 2~3 °C/s, tensile strength increased by approximately 10 % for Astaloy CrA with 0.8 %C, and an improvement in hardness of around 20 %. The impact energy is significantly increased after high temperature sintering compared to conventional sintering.



a) Hardness. b) Ultimate tensile strength. c) Impact energy.

Figure 6. Mechanical properties of different material sintered at 1250°C with different cooling rates.

One of the most important properties required for producing competitive PM components is dimensional consistency. The standard deviations of DC for the outer diameter of an oil pump rotor, a component commonly using sinter-hardened material were investigated in a study by Jie Yang and others [10], as shown in Figure 7. Both Astaloy CrM and Astaloy CrA materials show less dimensional scatter compared to other commercial sinter-hardened materials. Astaloy CrM has the lowest dimensional scatter due to being pre-alloyed, and without the addition of Cu there is no segregation.

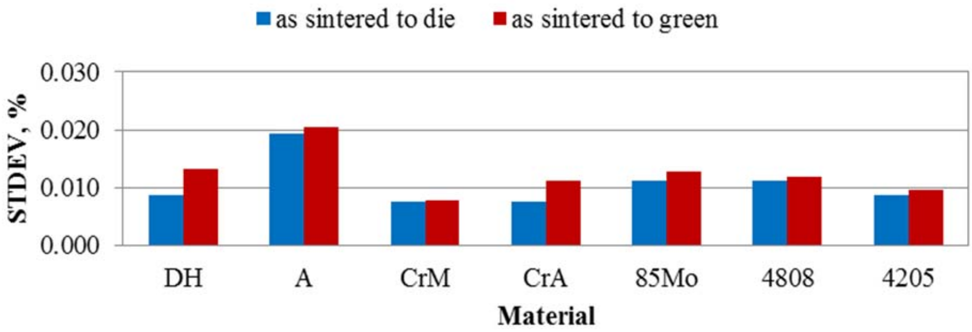


Figure 7. Standard Deviations of DC for the OD of rotors with different sinter-hardened material [10].

The high mechanical properties and dimensional consistency achieved with Astaloy CrM and Astaloy CrA, two Cr alloyed materials, make them very suitable for demanding applications requiring high performance as well as tight tolerance. For example, synchronizing hubs used in manual transmission (MT) and dual clutch transmission (DCT) have complex shapes and high performance requirements. A synchronizing hub is required to function as a mechanical connection during the gear change in a transmission. As a consequence, it requires high strength to withstand the transmitting torque, and high hardness to withstand the sliding from the sleeves. The edge face of the boss also needs high hardness to withstand sliding from the opposite materials. A study [11] looking at the combination of Astaloy CrM with a sinter-hardening process for this application has shown it is a cost-effective solution that provides high strength and hardness, with low dimensional distortion. In addition, the wear resistance of Astaloy CrA can be improved significantly compared to a Fe-Cu-C alloying system by using steam treatment and the nitrocarburising process. This makes it possible for the material to create less wear on the belt pulley used in water pumps and fuel injection system, as well as the belt itself [12].

5. Conclusions

PM technology has environmental advantages when compared to wrought steel technology, and Chromium alloyed PM material has less environmental impact when compared to material containing Ni. Chromium alloyed PM steels are also cost-effective and versatile materials. They can be utilized to manufacture PM components with high mechanical performance, as well as excellent dimensional consistency by using different processing methods. This material responds very well to the sinter-hardening process, resulting in high strength and high hardness. High temperature sintering can further improve the performance level, especially for toughness and ductility. High performance, excellent dimensional consistency, as well as advantages in sustainability makes chromium alloyed material very suitable for applications with high demands such as synchronizing components, cam lobes, belt pulleys and ring gears.

6. Acknowledgment

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7. Reference

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