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Properties of Cr-alloyed PM Steel after Different Sintering and Heat Treatment Operations

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***Abstract*— Water-atomized steel powder grades pre-alloyed with Cr are cost effective, robust and versatile materials which are suitable for PM steel parts in demanding structural applications. By choosing the right processing route, these materials enable efficient manufacturing of PM components with high mechanical performance. In this paper properties obtained after different sintering and heat treatment operations are presented for two different Cr-alloyed steel powder grades. Results from high temperature sintering, sinter-hardening and low pressure carburizing tests are reviewed with focus on static mechanical data, bending fatigue properties and microstructures.**

Keywords - chromium; pre-alloying; sintering; heat treatment; mechanical properties

I. Introduction

Chromium is extensively used as alloying element in conventional low-alloy steel mainly due to its high hardenability effect, low cost and because Cr-alloyed steels are easy to recycle. However, the usage of Cr in low-alloy PM steel has until recently been very limited as a result of the difficulty to use oxidation sensitive alloys in the PM manufacturing processes. The development of new water-atomized powder grades pre-alloyed with Cr during the last two decades [1-3] has changed the situation and these materials are today well-established in the manufacturing of PM steel components.

Sinter-hardening in continuous mesh belt furnaces is an efficient way to produce PM parts with high hardness and strength without the need for subsequent heat treatment. Mesh belt furnaces are however restricted in operating temperature (max around 1150°C) which can be a limitation, since higher sintering temperature enables improved PM part properties. Furnace concepts with both high temperature sintering and rapid cooling features, combined with high productivity, can thus be beneficial to use in PM part manufacturing for high performance applications. Such a furnace concept has recently been introduced in the mass production of PM transmission synchronizer hubs based on steel powder pre-alloyed with Cr [4, 5]. The benefits of using Cr-alloyed powder grades in sinter-hardening and high temperature sintering processes have also been highlighted in several earlier studies [6-9].

Vacuum heat treatment is an attractive process alternative to conventional gas-carburizing for PM steel parts in general and Cr-alloyed PM steel parts in particular [10, 11]. Low pressure carburizing (LPC) combined with high pressure gas quenching (HPGQ) provides good case depth control and relatively low part distortion. Moreover, there are no oxidation issues due to interaction with an oxygen rich gas atmosphere and no need for post-process cleaning of the PM parts as in the case of oil quenching.

II. Experimental Procedure

Two commercial water-atomized steel powders, Astaloy™ CrA pre-alloyed with 1.8 wt% Cr and Astaloy CrM® pre-alloyed with 3 wt% Cr + 0.5 wt% Mo, were used as base materials in the investigation.

Test mixes were prepared by adding different amounts (0.3-0.8 wt%) of graphite (C-UF from Kropfmühl) and lubricant (0.6 wt% Lube E) to the base powders and mixing in a laboratory mixer. Copper powder (-325 mesh) and nickel powder (Inco-123) were also used as alloying additives in some of the mixes.

Standard test bars for tensile testing (ISO 2740), impact testing (ISO 5754) and fatigue testing (ISO 3928) were produced from the powder mixes by uniaxial compaction with a pressure of 700 MPa. Higher compaction pressure (800 MPa) in combination with heated (80°C) tool die was used for one of the test mixes (AstCrA-0.75%C-UF for high temperature vacuum sintering).

Sintering trials were performed in a laboratory mesh belt furnace equipped with rapid cooling

unit. The test specimens were sintered at 1120°C for 30 min in N_2/H_2 (90/10) and different cooling rates (0.8/2.5°C/s) after sintering were applied. High temperature sintering trials were done in batch furnaces at 1250°C for 30 min in either N_2/H_2 (90/10) or at low pressure (10 mbar N_2). Cooling rate after sintering in N_2/H_2 was around 0.5°C/s, while forced cooling (>5°C/s) with high gas pressure (2 bar N_2) was applied after sintering in the vacuum furnace.

Case-hardening by LPC and subsequent HPGQ (20 bar N_2) was done in a two-chamber vacuum furnace. The heat treatment temperature was 965°C and C_2H_2 diluted with N_2 was used as carburizing gas. The LPC trials were performed on high temperature sintered (1250°C, 30 min) test bars and demonstrator components consisting of sintered transmission gears (see Fig. 1). Tempering after the LPC trials (as well as all sinter-hardening trials) was done at 200°C for 60 min in air.

Static mechanical data were evaluated through Vickers hardness measurements, tensile tests and Charpy impact tests. Fatigue testing (4-point plane bending) was done using the staircase method to evaluate the endurance limit at 2 million cycles at fully reversed loading (R = -1). Microstructures were studied through light optical microscopy.

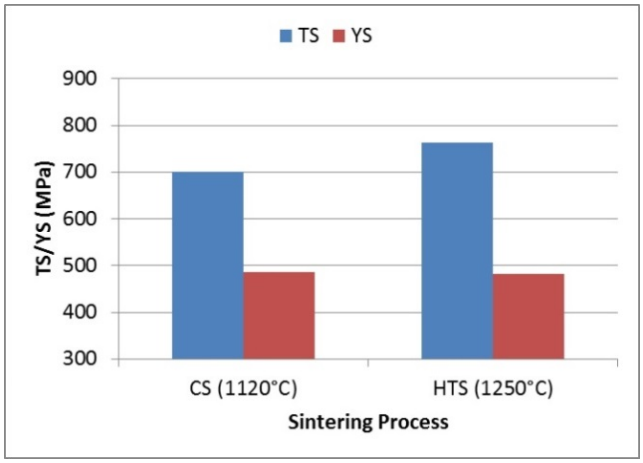


Fig. 1. M32 PM transmission gear used as test component in LPC heat treatment trials.

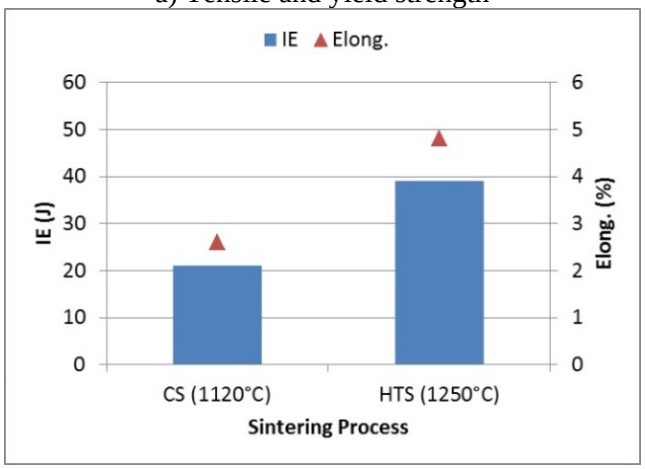
III. Results and Discussion

A. Conventional and high temperature sintering

Mechanical properties after high temperature sintering (HTS) in N_2/H_2 atmosphere of specimens based on AstCrA-0.8%C-UF are shown in Fig. 2. Corresponding properties after conventional sintering (CS) at 1120°C are included for comparison. Sintered density (SD) is somewhat higher after HTS (7.17 g/cm^3) than after CS (7.06 g/cm^3). Yield strength and hardness (around 210 HV10) is basically equivalent after the two processes, while the tensile strength is improved by almost 10% after sintering at the higher temperature. Elongation and impact strength values are significantly higher after high temperature sintering compared to after conventional sintering. The microstructure consists of fine pearlite after both processes, with more rounded pore shape and somewhat smaller pore size in the specimens that were high temperature sintered. This pore rounding effect explains the large improvement in toughness and ductility after sintering at the higher temperature.



a) Tensile and yield strength



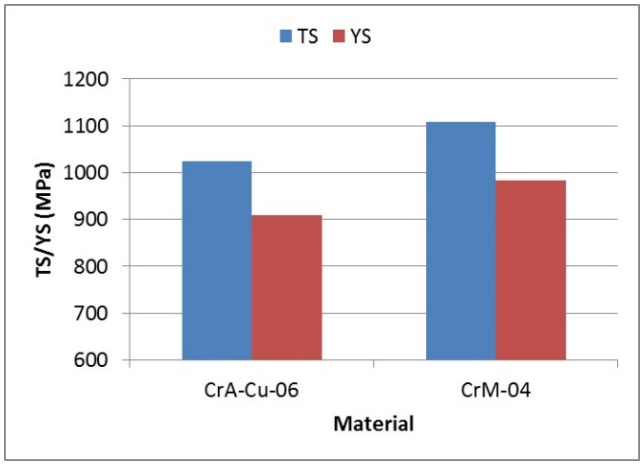
b) Impact energy and elongation

Fig. 2. Properties of AstCrA-0.8%C-UF specimens after different sintering trials (SD = 7.1-7.2 g/cm^3).

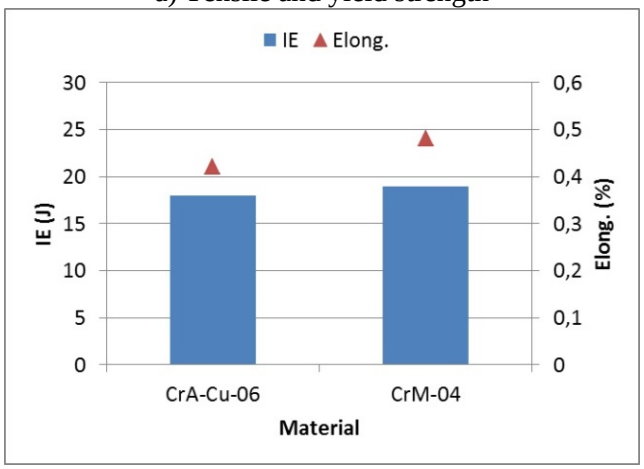
B. Sinter-hardening

Mechanical properties after sinter-hardening in a mesh belt furnace for specimens based on AstCrA-2%Cu-0.6%C-UF (CrA-Cu-06) and AstCrM-0.4%C-UF (CrM-04) are presented in Fig. 3. The specimens have similar density (around 7.05 g/cm^3). Hardness is somewhat higher for the AstCrM material (358 HV10) than for the AstCrA material (345 HV10). The AstCrM

material also has higher tensile and yield strength values compared to the AstCrA material. Impact strength and elongation values are comparable for the two materials. The microstructure of the AstCrA material consists of martensite mixed with about 25% bainite, whereas the AstCrM material has basically a fully martensitic microstructure with only traces of bainite.



a) Tensile and yield strength



b) Impact energy and elongation

Fig. 2. Properties of AstCrA and AstCrM based materials after sinter-hardening (1120°C, 30 min) with cooling rate 2.5°C/s (SD = 7.05 g/cm^3).

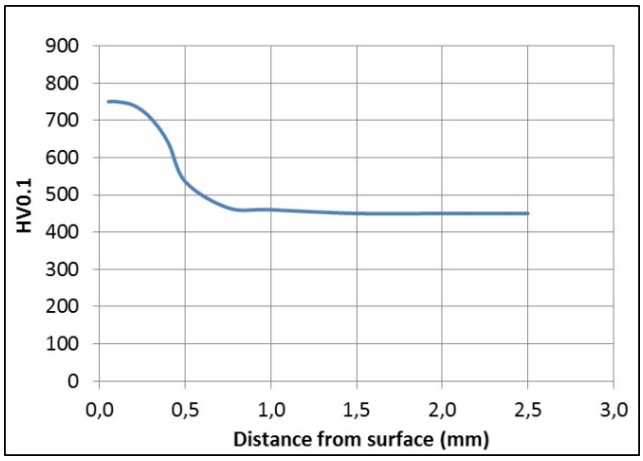
The combination of high temperature vacuum sintering and forced cooling resulted in excellent mechanical properties for test specimens based on AstCrA-0.75%C-UF (see Table 1). Sintered density is 7.28 g/cm^3 and carbon content after sintering 0.58% C. The microstructure is fully martensitic with small and rounded pores, which are features that provide these nice performance characteristics where very high hardness and strength values are combined with relatively high impact strength.

Table 1. Properties of AstCrA-0.75%C-UF specimens (SD = 7.28 g/cm^3) after high temperature vacuum sintering (1250°C, 30 min) and rapid cooling (>5°C/s).

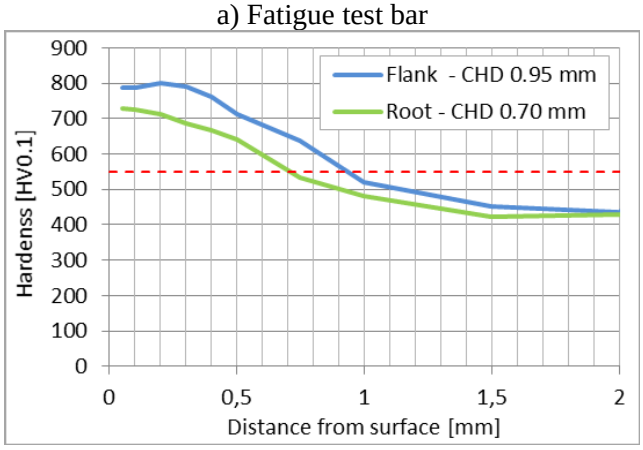
HV10	TS (MPa)	YS (MPa)	Elong. (%)	IE (J)
455	1301	1203	0.33	25

C. Low pressure carburizing

Case-hardening by LPC was done on fatigue test bars (SD = 7.25 g/cm^3) and gear specimens (see Fig. 1, SD = 7.20 g/cm^3) based on AstCrA-2%Ni-0.3%C-UF. Carbon content after sintering was in the range of 0.20-0.25% C. The microhardness profiles of the case-hardened samples are shown in Fig. 3. Test bars and gears have similar surface hardness values (700-800 HV0.1) and core hardness values (430-450 HV0.1). These gear teeth core hardness values are in the optimum range for reaching high fatigue performance [12].



a) Fatigue test bar



b) Transmission gear specimen

Fig. 2. Microhardness profiles of test samples based on AstCrA-2%Ni-0.3%C-UF after case-hardening by the LPC process (SD = 7.20-7.25 g/cm^3).

The microstructures after case-hardening are fully martensitic at the specimen surfaces and mixed martensitic/bainitic (with also some Ni-rich austenite) in the specimen cores. There are thicker

martensitic surface layers, and hence also larger case-hardening depth (CHD), in the gear specimens than in the test bars. This is due to that different process parameters were applied in the LPC process for the two specimen types.

High surface hardness (470 HV10) and very good fatigue endurance limit ($\sigma_{A,50\%}$ = 440 MPa) were obtained in the evaluation of the case-hardened test bars.

IV. CONCLUSIONS

The performed investigations demonstrate that steel powder grades pre-alloyed with Cr are versatile materials which can be utilized to manufacture PM steel parts with high mechanical properties by means of different process routes.

By using the Cr-materials in combination with for example sinter-hardening or an integrated high temperature vacuum sintering and low pressure carburizing process, cost-effective manufacturing of high performance PM steel components (e.g. synchronizer hubs and automotive transmission gears) is feasible.

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