Mechanical performance of Cr-alloyed PM steel after different sintering and heat treatment operations

Ola Bergman*, Dimitris Chasoglou and Magnus Dahlström

Research & Development, Höganäs AB, SE-263 83 Höganäs, Sweden

Main benefits of the PM technology versus conventional steel making processes in the manufacture of structural steel parts are high material utilization, low energy consumption and short production time. These benefits are fully exploited by choosing the right combination of material and processing route to get the required mechanical properties at a low production cost. Powder grades pre-alloyed with Cr are robust and cost effective materials which are suitable for high performance PM steel components. This paper presents mechanical properties of Cr-alloyed PM steel obtained after different processing routes, including high temperature sintering, sinter-hardening and heat treatment by low pressure carburizing. Static mechanical data are presented as well as results from plane bending fatigue tests. Microstructures are also shown and correlated with the mechanical properties obtained for the respective processing routes.

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. By pre-alloying, the activity of Cr is lowered compared to the situation when Cr-rich additives (e.g. ferrochrome, master alloys) are used, which makes the materials less oxidation sensitive. This enables sintering of PM steel grades pre-alloyed with Cr in conventional mesh belt production furnaces with good results, provided that a protective atmosphere with low oxygen content is utilized. It is recommended to use N_2 based atmospheres containing up to 10% H_2 and with dew points preferably below $-30°C$ when sintering these materials at the commonly applied temperature 1120°C [4,5]. Other benefits of having Cr in pre-alloyed form in PM steel are that robust material performance (e.g. dimensional consistency) is provided and that excellent mechanical properties can be obtained by various processing routes.

Continuous mesh belt furnaces are normally used for sintering in the production of PM steel parts as these furnaces enable high productivity and thus cost effective manufacturing. Today many belt furnaces are also equipped with a rapid cooling unit which gives the possibility to perform sinter-hardening. Hereby, PM parts with high hardness and strength can be produced directly in the sintering process 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. Powder grades pre-alloyed with Cr are suitable for sinter-hardening and their mechanical performance can also be boosted to very high levels by the application of high temperature sintering [6–8].

Conventional heat treatment (e.g. gas carburizing) of PM parts is usually more challenging and requires adjusted process

Corresponding author: Bergman, O. (ola.bergman@hoganas.com)

parameters compared to solid steel parts, since penetration of the process gas in the PM part pore system affects the results. Vacuum heat treatment, where low pressure carburizing is combined with high pressure gas quenching, is therefore an attractive alternative as it allows better case depth control and also less part distortion [9]. Furthermore, vacuum heat treatment is suitable for Cr-alloyed PM steel parts as oxidation issues due to interaction with an oxygen rich gas atmosphere are avoided.

Experimental procedure

Two commercial water-atomized steel powders pre-alloyed with Cr (and also Mo for one of the powders) were used as base materials in the investigation. Chemical composition and compressibility of these materials are presented in Table 1.

Test mixes were prepared by adding graphite (Kropfmühl UF4) and lubricant (Lube E) to the base powders and mixing in a laboratory mixer. Copper powder (−325 mesh) and nickel powder (Inco-123) were also used in two of the mixes. The compositions of the mixes are shown in Table 2.

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. Three different sintering trials were performed with process parameters according to Table 3. The conventional sintering (CS) and sinter-hardening (SH) trials were done in a mesh belt furnace equipped with a rapid cooling unit, while the high-temperature sintering (HTS) trial was done in a lifting hearth batch furnace. Heat treatment trials were performed in vacuum furnaces (see process parameters in Table 4). Through-hardening (TH) was done on conventionally sintered test bars by quenching in oil or gas

TABLE 1

Nominal chemical composition and compressibility of evaluated steel powders.

Powder	Fe [%]	Cr [%]	Mo [%]	GD[a] [g/cm³]
Astaloy™ CrA	Base	1.8	–	7.05
Astaloy CrM®	Base	3.0	0.5	6.98

[a] Green density at 600 MPa compaction pressure with lubricated die.

TABLE 2

Composition of the test mixes used in the investigation.

Material ID	Base powder	C-UF [%]	Cu-325 [%]	Ni-123 [%]	Lube E [%]
CrA-04	Astaloy CrA	0.4	–	–	0.6
CrA-08	Astaloy CrA	0.8	–	–	0.6
CrA-Ni-03	Astaloy CrA	0.3	–	2.0	0.6
CrA-Cu-06	Astaloy CrA	0.6	2.0	–	0.6
CrM-04	Astaloy CrM	0.4	–	–	0.6

TABLE 3

Sintering process trials.

Sintering process	T [°C]	Time at T [min]	Atmosphere	CR [°C/s]	Material
CS	1120	30	N₂/H₂ (90/10)	0.8	CrA-08
HTS	1250	30	N₂/H₂ (90/10)	0.5	CrA-08
SH	1120	30	N₂/H₂ (90/10)	2.5	CrA-Cu-06 CrM-04

TABLE 4

Vacuum heat treatment process trials.

Heat treat. process	T [°C]	Time at T [min]	Atmosphere	Quench media	Material
TH-1	920	30	N₂ (10 mbar)	Oil (60 °C)	CrA-04
TH-2	920	30	N₂ (10 mbar)	N₂ (20 bar)	CrA-04
CH	965	55	N₂ (10 mbar) + C₂H₂[a]	N₂ (20 bar)	CrA-Ni-03

[a] Acetylene diluted with nitrogen was used as carburization gas.

after austenitization in vacuum. Case-hardening (CH) was done after high-temperature vacuum sintering (1250°C, 30 min) by low pressure carburization (LPC) followed by high pressure gas quenching. Tempering after all hardening processes (SH, TH, CH) was done at 200°C for 60 min in air.

Mechanical properties after sintering and heat treatment were evaluated through Vickers hardness measurements, tensile tests and Charpy impact tests. Fatigue testing (4-point plane bending) was also done after the case-hardening trial, using the staircase method to evaluate the endurance limit at 2 million cycles and fully reversed loading ($R = -1$). Carbon analyses were made in Leco instruments and sintered density was measured in accordance with Archimedes' principle. Microstructures were studied through light optical microscopy.

Results

Evaluation results for test specimens from the sintering process trials are shown in Table 5 and also in Figs. 1–3. Material CrA-08 has slightly lower carbon content and higher density after the HTS process than after the CS process. Both hardness and yield strength of the material is basically equivalent after these two processes, while the tensile strength is improved by almost 10% after sintering at the higher temperature (Fig. 1a). Furthermore, elongation and impact strength values are significantly higher after high temperature sintering compared to after conventional sintering (Fig. 1b). The microstructure of CrA-08 consists of fine pearlite (Fig. 3a) after both sintering processes, with more rounded pore shape and somewhat smaller pore size in the specimens that were high temperature sintered.

The materials CrA-Cu-06 and CrM-04 have similar density and about the same carbon loss after the sinter-hardening process. Hardness is somewhat higher for CrM-04 than for CrA-Cu-06. Material CrM-04 has also higher tensile and yield strength values compared to the CrA-Cu-06 material (Fig. 2a), while impact strength and elongation values are comparable for the two materials (Fig. 2b). The microstructure of CrA-Cu-06 consists of martensite mixed with about 25% bainite (Fig. 3b), whereas CrM-04 has basically a fully martensitic microstructure with only traces of bainite (Fig. 3c).

TABLE 5

Carbon content, sintered density (SD) and hardness of test specimens after different sintering process trials.

Material	Sintering process	C [%]	SD [g/cm³]	Hardness [HV10]
CrA-08	CS	0.71	7.06	207
CrA-08	HTS	0.65	7.17	211
CrA-Cu-06	SH	0.54	7.05	345
CrM-04	SH	0.35	7.07	358