Performance Characteristics of Cost Effective Sinter Hardening Materials

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ABSTRACT

Sinter hardening of PM components is a well established and cost effective alternative to secondary heat treatment as one step in the manufacturing chain can be eliminated. However, during the last years alloys suitable for sinter hardening have been facing increased cost pressure due to increases and fluctuations in prices of nickel and molybdenum. Therefore, there is an increasing interest for availability of more cost effective low alloy steel powders that realize a compromise between compressibility and hardenability. The purpose of this paper is to present both static and dynamic properties achievable with a number of cost effective low alloy steel powders after sinter hardening.

INTRODUCTION

The development of new materials and cost effective processes are two main factors that contributed to the growth of PM during the last decades. Sinter-hardening , which utilises high performance materials in combination with an accelerated post sintering cooling rate, is one example of such material and process development (1,2,3). As this technique is a one step process it combines good manufacturing economy with the ability to achieve a unique combination of mechanical properties.

By controlling the post sintering cooling rate, the microstructure can be manipulated to form the required amount of martensite to obtain the desired mechanical properties. By increasing the hardenability of the material large amounts of martensite can be still obtained at lower cooling rates. Alloying elements such as molybdenum, chromium, nickel and copper all promote hardenability. In recent years there has been a dramatic rise in raw material costs of especially molybdenum, nickel and copper. These are typical alloying elements used in applications utilizing traditional sinter and sinter hardened PM materials. Therefore there is a continuously growing interest to utilize more cost effective alloying elements such as chromium and leaner nickel /molybdenum alloyed steels.

In this paper the influence of alloying system and cooling rate on both microstructure and mechanical properties will be discussed. Besides composition and microstructure, density and mass play an important role to achieve the desired properties. Therefore properties after sinter hardening were evaluated at two density levels, 7.0 $glcm^3$ and 7.15 $glcm^3$. The influence of mass on the resulting microstructure and hardness after sinter hardening will also be discussed.

EXPERIMENTAL PROCEDURE

Materials

In order to compare the sinter hardening performance of two pre-alloyed Cr alloyed PM steels and two new cost effective Ni/Mo steels with a conventional Ni/Mo steel, Astaloy A, five different powder mixes were prepared. The base powders used for the mixes were Astaloy A , Astaloy CrL, Astaloy CrM, Astaloy LH and Distaloy LH. The chemical composition of the different powder mixes is shown in Table 1 below. Astaloy A is a fully pre-alloyed powder with 1,9% Ni and 0,5% Mo. Astaloy CrL is a fully pre-alloyed powder containing 1,5% Cr and 0,2% Mo whereas Astaloy CrM is pre-alloyed with 3% Cr and 0,5% Mo. Astaloy LH is a

new fully pre-alloyed powder with 0,9% Ni and 0,9% Mo. The Distaloy.LH powder is based on the fully pre-alloyed Astaloy LH to which 2% Cu has been diffusion alloyed. The identification codes for these mixes used in this paper are also shown in this table. 0.60 % Kenolube was added as lubricant. The copper admixed to the different was -325 mesh electrolytic copper powder, and the graphite used in all cases was UF-4 from Kropfmühl.

Table 1: Chemical composition of investigated powder mixes.

Base powder	**Identification code**	**Ni %**	**Mo %**	**Cr %**	**Cu %**	**Gr. %**	**Lub. %**
Astaloy CrL	CrL		0,2	1,5	2,0**	0,85	0,6
Astaloy CrM	CrM		0,5	3,0		0,45	0,6
Astaloy A	AA	1,9	0,5		2,0**	0,85	0,6
Astaloy LH	ALH	0,9	0,9		2,0**	0,85	0,6
Distaloy LH	DLH	0,9	0,9		2,0*	0,85	0,6

*Diffusion bonded ** Admixed

Processing conditions

Test specimens, tensile test bars, impact energy bars and plane bending fatigue specimens according to ISO standards were compacted in a Tonitechnik 100 ton, semi-automatic laboratory press, to two different density levels, 7.00 g/cm^3 and 7.15 g/cm^{3}by conventional compaction. It is important to notice that the compaction pressure required to reach the desired density levels will vary considerably with the base material selected.

Sintering was carried out in a laboratory sintering furnace from Cremer equipped with rapid post sintering cooling system to be able to accelerate the cooling capabilities of the continuous belt furnace to the desired cooling rate. The sintering temperature used was set to 1120 ºC. Sintering time was 30 min at temperature and the atmosphere used was 90/10 mix of nitrogen and hydrogen. Two different cooling rates were used, 0,8ºC/s for reference and 2,5 ºC/s for sinter hardening. After sintering tempering was carried out at 200º C for 60 minutes in air.

After the final tempering operation, apparent hardness measurements were performed on the surface of the specimens using the Rockwell C scale for comparison purposes. Tensile testing was performed in a MTS Sintech 20D tensile testing machine. Impact energy tests were carried out in a Charpy tester. Plane bending fatigue tests were carried out on un-notched compacted specimens at a fully reversed load ratio of R=-1. Endurance limit was evaluated at 2 million cycles.

HARDENABILITY

Alloy composition, carbon content and cooling rate have a strong influence on the final microstructure of the material. By utilizing powders alloyed with chromium, nickel, molybdenum and copper together with proper amounts of carbon completely martensitic structures can be formed after sintering at 1120ºC already at moderate cooling rates, 1.5~2.5ºC/s.
To investigate the hardenability specimens were pressed to 7.0 g/cm^3 and sintered in $90N_2/10H_2$ atmosphere for 20 minutes at 1120ºC. They were then held at 1120ºC in vacuum in the dilatometer for 10 minutes before they were cooled at well defined cooling rates down to room temperature. Fractions of martensite were determined by light optical microscopy of polished and etched sample cross sections.

Figure 2 shows the amount of martensite obtained for the DLH and AA materials using different cooling rates during sintering. The hardenability behaviour is similar for the two materials. The AA material has a somewhat better response at slow cooling rates (>0.5ºC/s), while DLH ensures higher levels of martensite at cooling rates in the range 1.5-3ºC/s.

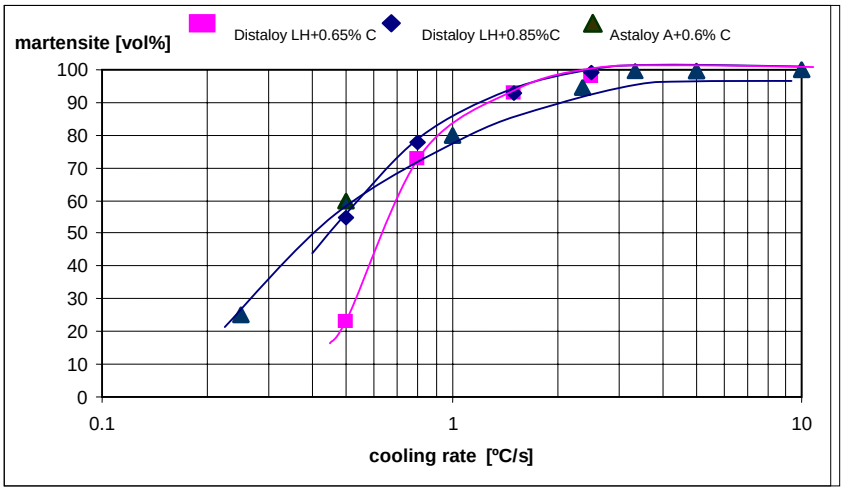
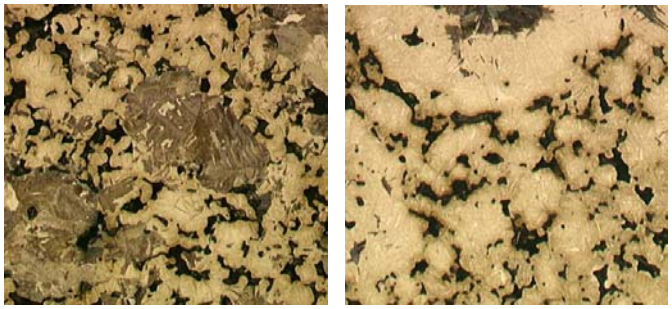


Figure 2. Martensite content vs. cooling rate for Distaloy LH+0.65% and 0.85% graphite and Astaloy A+2%Cu+0.65% graphite.

Figure 3 below shows micrographs of etched structures in DLH. In the micrographs the bright regions are martensite, and the dark brown regions are bainite. The images clearly show that high levels of martensite can be obtained at moderate sinter hardening cooling rates (~1.5ºC/s).



Distaloy LH+0.77C, 0.5ºC/s Distaloy LH+0.78C, 1.5ºC/s

Figure 3. Microstructure of Distaloy LH after different cooling rates; 0.5ºC/s and 1.5ºC/s.

In Figure 4 hardenability curves for the CrL material is presented. As can be seen cooling rates >2ºC/s are necessary, otherwise pearlitic/ bainitic structures are obtained. If high martensite contents are requested also for slower cooling rates, Cu can be admixed. This significantly improves the response at low cooling rates.

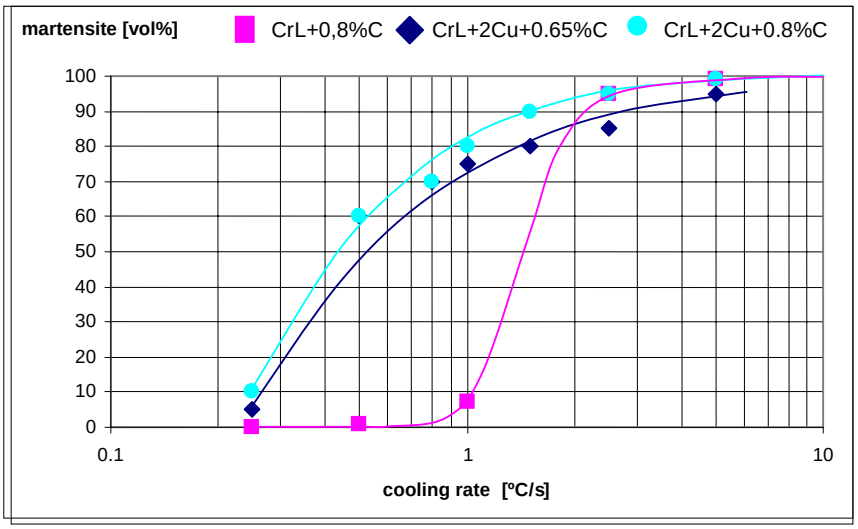
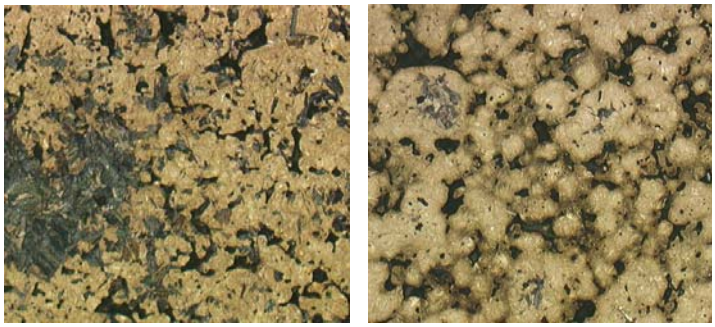


Figure 4. Martensite content vs. cooling rate for Astaloy CrL with and without 2%Cu.

Figure 5 shows microstructures obtained for CrL with and without an addition of 2% Cu after sinter hardening with a cooling rate of 2.5ºC/s. As can be seen the microstructure in the specimen without Cu is pearlitic/bainitic while the Cu containing material is mainly martensitic with some presence of bainite.



Astaloy CrL+0.69C, 2.5ºC/s Astaloy CrL+2Cu+0.71C, 2.5ºC/s

Figure 5. Astaloy CrL+0.70% C with and without 2% Cu. Cooling rate; 2.5ºC/s.

The more high alloyed CrM shows good hardenability already at 0.4% graphite, Figure 6 below. At 0.5% graphite the hardenability is excellent with a stable martensitic plateau from a cooling rate of 1ºC/s. At lower cooling rates there will be some fine bainite present. The high stability in microstructure makes CrM a suitable choice when sinter hardening parts with both thin and more massive sections, and a requirement for high strength.

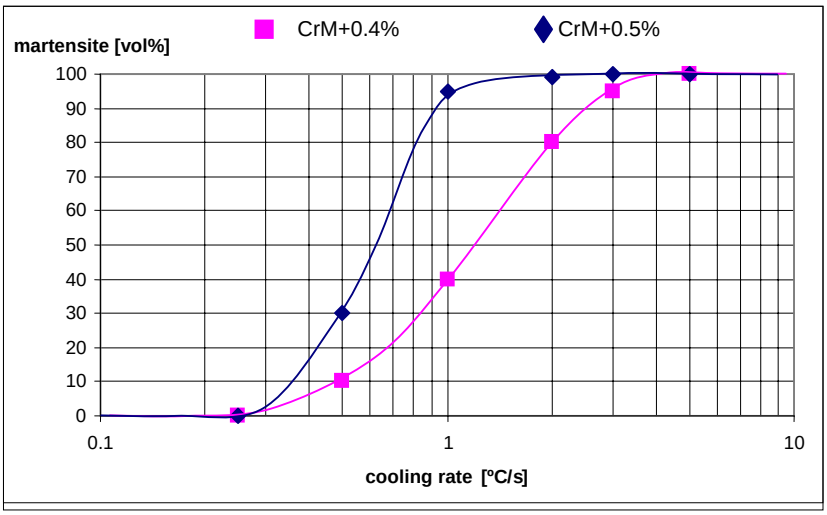


Figure 6. Martensite content vs. cooling rate for Astaloy CrM with 0.4% C and 0.5%C.

RESULTS AND DISCUSSION

A comparison of the hardness levels obtained at the two different density levels is shown in Table 4. As can be seen the hardness has increased for all materials when the density is increased from 7.00 to 7.15 g/cm^3 which is to be expected. The hardness levels obtained for the CrM material at the lower density level is the same as for the CrL material and slightly lower compared to the other materials. This is mainly due to the lower carbon content, 0.45%. However, at the higher density level the CrM material shows comparable hardness to the DLH and ALH materials.

Table 4. Hardness of cold compacted samples after sintering and tempering

	Density, g/cm^3	**Material**				
		CrL	**CrM**	**AA**	**DLH**	**ALH**
Hardness, HRC	7.00	33	33	35	37	35
Hardness, HRC	7.15	34	40	37	40	41

The mechanical properties obtained after sinter hardening of the five materials are shown in Table 5.

Table 5. Mechanical properties of cold compacted samples after sintering and tempering

Material	**CrL**	**CrM**	**AA**	**DLH**	**ALH**
Density 7.00 g/cm^3					
Tensile strength, MPa	850	955	889	955	925
Yield strength, MPa	800	928	815	825	840
Impact energy, J	16	15	16	17	17
Bending fatigue strength, Mpa	290	320	270	295	290
Density 7.15 g/cm3					
Tensile strength, MPa	935	1060	940	1060	1015
Yield strength, MPa	905	1020	910	908	935
Impact energy, J	19	18	19	20	20

As can be seen all properties increased with increasing density. The ultimate tensile strength increased about 10% for the two Cr alloyed and the DLH and ALH materials when density

was increased from 7.00 to 7.15 g/cm^3. The CrM material and the DLH material achieved the same tensile strength at both density levels, 955 and 1060 MPa respectively. The CrL and AA material achieved comparable results at both density levels and about 10 % lower compared to the other three materials. It is also worth to point out that the the carbon content of the CrM material was 0.45% compared to 0.85% for the other materials and without any Cu addition.

The increase in density resulted in improvements in yield strength of about 10% for all materials. The CrM material obtained the highest yield strength at both density levels, 928 and 1020 MPa respectively. All the other materials obtained similar yield strength at the two density levels, 800 to 840 MPa at the lower level and 905 to 935 at the higher density level.

By comparing the impact energies obtained for the five materials it can be seen that the DLH and ALH materials achieved the highest level, 17 J at the lower density and 20J at the higher density. The other three materials obtained slightly lower impact energy at both densities.

The increased cooling rate also has a positive effect on plane bending fatigue strength. CrM obtained the highest fatigue strength, 320 MPa at the lower density level. The CrL and LH based materials obtained similar fatigue strength levels, 290-295 MPa compared to 270 MPa for material A. It should be pointed out that bending fatigue strength levels could be further increased by combining increased cooling rate with sintering at higher temperature.

The dimensional change obtained for the five materials during sintering is shown in Table 6. As can be seen the materials containing Cu all show a swelling of about 0,2-0,3 % , which is due to alloying with Cu which promotes growth during sintering. Regarding CrM it shows a slight shrinkage during sintering with a dimensional change close to zero.

Table 6. Dimensional change for the different materials at density 7.00 g/cm^3

Material	**CrL**	**CrM**	**AA**	**DLH**	**ALH**
DC, %	0,23	-0,02	0,39	0,32	0,33

INFLUENCE OF SIZE AND MASS

Slugs with an outer diameter of 40 mm and varying heights, 10 , 15, 20 and 30 mm, were compacted to simulate the different sizes of components manufactured in the PM industry. In this study the DLH mix outlined in Table 1 was compared with a mix containing 0,65%C and 1,5% Cu in order to see the influence of carbon, copper and mass effect on the resulting microstructure. The slugs of the two powder mixes were compacted to a green density of 7.00 g/cm^3. Sintering was performed for 30 minutes at 1120°C in a 90/10 N_2/H_2 atmosphere. The cooling rate of the furnace was set to correspond to 1.5ºC/s for the smallest slugs. The slugs were then tempered at 200°C for 1 hour in air. Apparent hardness and microstructure were then evaluated for each slug size.

The results are summarized in Table 6 below. As can be seen the DLH material obtained a hardness level exceeding 35 HRC when the mass increased from 88 g to 264 g. For the other material containing 1,5%Cu and 0,65%C the hardness decreased continuously with increasing mass. By comparing the microstructures achieved for the two materials when the mass is increasing, it is clear that the amount of martensite formed has decreased significantly with increasing mass for the material with the lower amount of Cu and C. The martensite content is reduced from almost 100 % for the smallest slug to an almost completely bainitic

microstructure for the largest slug. The DLH material on the hand showed a mainly martensitic structure for all slug sizes.

Table 7. Surface hardness and vol % martensite after sinter hardening of slugs with 40 mm diameter with different heights and weights

	Slug size (O.DxH), mm	40 x 10	40 x 15	40 x 20	40 x 30
	Weight, g	88	126	176	288
Material	Eff. cooling rate, °C/s	1.5	1.3	1.2	1.0
DLH (1.5%Cu)+0.65%C	Vol. % Martensite	90-93	70-75	65-70	2-5
	Hardness, HRC	34	31	30	10
DLH+0.85%C	Vol. % Martensite	98	97	95	85
	Hardness, HRC	37	37	37	36

COMPARISON OF COST AND PERFORMANCE FOR DIFFERENT PM STEELS

The cost effectiveness of the pre-alloyed Cr materials relative to other sinter hardening grades makes these materials very competitive for new high performance sinter hardening applications. Table 8 clearly demonstrates the superior cost effectiveness of the CrL and CrM materials. Using DLH as a reference, the material cost for CrL and CrM can be up to 30% lower.

Table 8. Relative material cost index for the different PM materials, Quarter 1, 2008

Material	**CrL**	**CrM**	**AA**	**DLH**	**ALH**
Relative cost, %	67	74	103	100	98

CONCLUSIONS

The results presented in this paper show that the Cr-Mo pre-alloyed materials Astaloy CrL and CrM on one hand and the newly developed materials Distaloy LH and Astaloy LH on the other are suitable for sinter hardening applications. Both LH materials are cost effective sinter hardening solutions with high compressibility that can be sintered in any sintering atmosphere, including endothermic gas.

Astaloy CrM and Astaloy CrL are the most cost effective sinter hardening solutions when the sintering process can handle sintering of Cr in a proper way.

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