SINTER-HARDENING AND HEAT TREATMENT OF MATERIALS BASED ON ASTALOY CRM

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ABSTRACT

Increased mechanical property of sintered steels is the major factor for the introduction of PM components as substitute for wrought steels. Materials based on the newly developed grades prealloyed with chromium, Astaloy CrM and Astaloy CrL, reach, depending on processing conditions, static and dynamic properties comparable to those of conventional fully dense steels.

In this paper the influence of the sintering temperature combined with increased post-sintering cooling rate or heat treatments such as low pressure carburizing, on the static and dynamic properties of materials based on Astaloy CrM is presented. If high temperature is followed by rapid cooling a tensile strength of 1400 MPa (200 ksi) is achieved, while by combining high temperature sintering with low pressure carburizing a fatigue limit over 500 MPa (72 ksi) can be obtained. A study of the dimensional stability of Astaloy CrM gears manufactured under production condition is also discussed.

INTRODUCTION

Chromium is an alloying element with several advantages since it gives good hardenability, is relatively cheap and easy to recycle. Using Astaloy CrM, a water atomised iron powder grade prealloyed with 3% chromium and 0.5% molybdenum, high strength and hardness are obtained directly after sintering at 1120 °C (2050 °F). Due to its good hardenability, parts made of Astaloy CrM can be hardened, i.e. more than 50% martensite can be achieved in mesh belt sintering furnaces without copper additions. Sinter-hardened Astaloy CrM with 0.4% carbon and a density of 7.0 g/cm^3 achieves a tensile strength of 900 MPa with an elongation <0.5% and impact energy of 12-13 J when sintering at 1120 °C for 30 minutes and cooling at a rate of 2-3 °C/s [1]. The strength and toughness of Astaloy CrM can be raised by increasing the sintering temperature from 1120 °C (2050 °F) to above 1200 °C (2192 °F) mainly due to the formation of larger sintering necks, increased density and pore rounding. Further improvement can be obtained by combining high temperature sintering with rapid cooling or heat treatment such as carburising. Due to the affinity of chromium for oxygen, oxidation

can take place when carburising is carried out in gases such as Endogas or cracked methanol, therefore carburising in vacuum or plasma carburising are better alternatives.

Tight dimensional tolerances can be achieved with this material as the alloying elements, chromium and molybdenum, are prealloyed to the iron. This is advantageous especially for sinter-hardened parts as the high hardness obtained makes sizing operation difficult.

The purposes of this paper is:

a) To show the influence of sintering temperature and cooling rate on the static and dynamic properties of Astaloy CrM based materials with different carbon content and densities. Two sintering temperature were tested, 1250 °C (2282 °F) and 1300 °C (2372 °F), followed by cooling at 0.5-1 °C/s (0.9-1.8 °F/s) and 2-3 °C/s (3.6-5.4 °F/s);
b) To investigate the possibility of combining high temperature sintering with vacuum carburising in one step and to study the influence of this process on mechanical properties;
c) To evaluate the dimensional stability of Astaloy CrM when sintered at 1120 °C (2050 °F). To achieve this, the focus was placed on the dimensional scatter of a gear manufactured under production conditions.

MATERIALS

Six materials were investigated based on Astaloy CrM. The chemical composition of the base powder used is reported in Table I. The nominal composition of the studied mixes is reported in Table II.

Table I. Chemical composition of the investigated base powder.

	Cr wt%	**Mo wt%**	**C wt %**	**O wt%**	**Fe wt%**
Astaloy CrM	3.0	0.5	0.005	0.20	Bal.

Table II. Nominal composition of the investigated mixes

Mix No.	**Graphite wt%**	**A-wax wt%**	**Lube wt%**
1	0.5	0.8	
2	0.6	0.8	
3	0.5	0.75	
4	0.45		0.6
5	0.5		0.6
6	0.6		0.6

Kropmülf graphite UF4 (96-97% C) was admixed with the base powder in mix 1, 2, 4, 5 and 6, while Asbury graphite 1651 was used in mix 3. Amide wax grade was used in mixes 1, 2, 3 employed in the preparation of cold compacted specimen. Warm compacted specimens (mix 4, 5, 6) were based on Densmix® powder grades.

PROCESSING CONDITIONS

Influence of sintering temperature and cooling rate

Mixes 1, 2, 5 and 6 were used for studying the influence of high temperature sintering and cooling rate on the mechanical properties of Astaloy CrM. Mix 1 and 2 were pressed at room temperature to achieve a green density of 6.9 g/cm^3. Mixes 5 and 6 were warm compacted to achieve a green density

of 7.15 g/cm^3. Pressing was carried out in a semiautomatic laboratory press (Result type). For warm compaction both the powder and the tooling were heated to 120 °C (248 °F). The following sample geometries were pressed: tensile testing samples (ISO 2470-1986), impact energy samples (ISO 3325), modified ISO 5754 transverse rupture strength samples with size 90x12x6 mm (3.543x0.472x0.236 inch). As-sintered modified ISO 3928 test bars were used for fatigue tests [2].

Four sintering conditions were tested, as summarised in Table III. Sintering was carried out in a batch lifting earth furnace equipped with a unit for rapid cooling (Cremer type). All materials were tempered at 200 °C/390 °F for 60 minutes in air.

Table III. Sintering conditions

	Test 1	**Test 2**	**Test 3**	**Test 4**
Temperature	1250 °C/2282 °F	1250 °C/2282 °F	1300 °C/ 2372 °F	1300°C/2372 °F
Time	30 min	30 min	30 min	30 min
Cooling rate	0.5-1 °C/s 0.9-1.8 °F/s (normal cooling)	2-3 °C/s 3.6-5.4 °F/s (rapid cooling)	0.5-1 °C/s 0.9-1.8 °F/s (normal cooling)	2-3 °C/s 3.6-5.4 °F/s (rapid cooling)
Atmosphere	90-10 N_2-H_2	90-10 N_2-H_2	90-10 N_2-H_2	90-10 N_2-H_2

High temperature sintering combined with vacuum carburising

Mix 4 was used for investigating the mechanical properties that can be achieved with Astaloy CrM after high temperature sintering followed by carburising in vacuum. Mix 4 was warm compacted to achieve a green density of 7.15 g/cm^3. The specimens were sintered at 1300 °C (2372 °F) in a laboratory vacuum furnace for 30 min. Subsequently they were cooled at 1050 °C (1922 °F). At this temperature the samples were carburised with acetylene gas for a total of 8 minutes. Thereafter, cooling was performed in an N_2 atmosphere at 2 bar pressure. In the next step, the samples were moved to another vacuum furnace, where they were heated at 950 °C for 15 min and then cooled with N_2 at 7 bar pressure. The samples were tempered at 200 °C (390 °F) for 60 min in air.

Evaluation of dimensional stability in production environment

Mix 3 was used to study the dimensional stability of a gear in a production environment. Tests were carried out at Pennsylvania Powdered Metal. The gear evaluated is shown in Figure 1. Outer diameter of the gear was 43 mm (1.693 inch), inner diameter 23 mm (0.906 inch) and height 12 mm (0.472 inch).



Figure 1. Investigated gear

One thousand gears were pressed to 6.85 g/cm^3 green density on a 60-ton Bliss press. These gears were then split into two 500-piece samples for sintering. Both group of samples were sintered in an Abbott 300 mm (12") belt furnace equipped with a unit for rapid cooling (Varicool) under the same conditions (30 min, 90/10 N_2/H_2, and 1120ºC) except for the cooling rate. Five hundred pieces were sintered with rapid cooling, and 500 were sintered and then cooled at normal rates.

After sintering, 50 gears were pulled from each sintering cycle at random and measured for dimensional change. The parts were measured on the outer diameter (OD) front to back (0º), and side to side (90º). Dimensional change was calculated from die to as-sintered.

RESULTS

Influence of high sintering temperature and cooling rate

Carbon and oxygen content, density, dimensional change, tensile and yield strength, elongation, transverse rupture strength, impact energy, hardness and microstructure were evaluated. Carbon content analysed after sintering is reported in Table IV.

Table IV. Analysed as-sintered carbon content

Material		Pressing technique	As sintered C%			
Mix No.	C-UF4 wt%		1250 °C		1300 °C	
			0.5-1 °C/s	2-3 °C/s	0.5-1 °C/s	2-3 °C/s
1	0.5	CC*	0.36	0.38	0.38	0.37
2	0.6	CC*	0.44	0.47	0.45	0.48
5	0.5	WC**	0.32	0.33	0.34	0.33
6	0.6	WC**	0.41	0.39	0.42	0.41

* cold compaction
** warm compaction

Analysed oxygen content was below 0.02% for all investigated materials.

Density measured after sintering at 1250 and 1300 °C is reported in Table V. When raising the sintering temperature from 1250 to 1300 °C, density is increased by 0.06 g/cm^3. This applies to the use of both cold and warm compaction.

Table V. Influence of sintering temperature and cooling rate on density

Mix No.	Pressing technique	Sintered density (g/cm^3)			
		1250 °C		1300 °C	
		0.5-1 °C/s	2-3 °C/s	0.5-1 °C/s	2-3 °C/s
1	CC	7.01	7.01	7.07	7.07
2	CC	7.02	7.02	7.08	7.08
5	WC	7.24	7.23	7.30	7.29
6	WC	7.24	7.23	7.30	7.29

Table VI shows the influence of increased sintering temperature and cooling rate on dimensional change. Tensile testing bars were used for evaluation of dimensional change. Dimensional change was calculated from green to as-sintered and is the mean of seven measurements.

Table VI. Influence of sintering temperature on dimensional change

Mix No.	Pressing technique	Dimensional change% Green-as sintered			
		1250 °C		1300 °C	
		0.5-1 °C/s	2-3 °C/s	0.5-1 °C/s	2-3 °C/s
1	CC	-0.76	-0.73	-1.08	-1.05
2	CC	-0.79	-0.78	-1.12	-1.11
5	WC	-0.60	-0.57	-0.89	-0.80
6	WC	-0.60	-0.58	-0.90	-0.85

Shrinkage is increased when raising the sintering temperature from 1250 to 1300 °C, which is in agreement with the higher density, while it decreases slightly when raising the cooling rate from 0.5-1 °C/s to 2-3 °C/s at both sintering temperatures.

As-sintered carbon content is reported in figures 2-14. Hardness Vickers (HV10) is reported in figures 2 and 3.

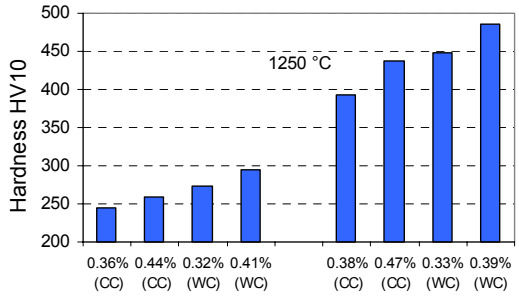


Figure 2. Hardness Vickers, HV10 Cooling at 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right).

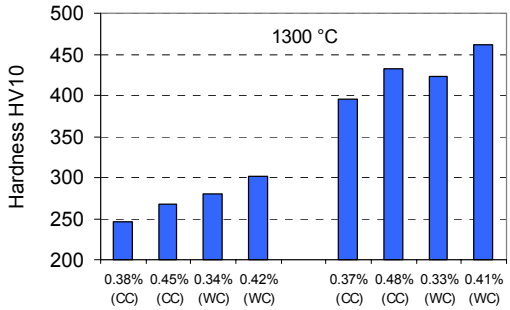


Figure 3. Hardness Vickers, HV10. Cooling at 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right).

Rockwell hardness HRB was measured on material 1 and 2 (cold compacted) with 0.5 and 0.6% graphite respectively after sintering at 1250 and 1300 °C and cooling at 0.5-1 °C/s. The results obtained are summarised in Table VII.

Table VII. Hardness HRB, cooling at 0.5-1 °C/s

Mix No.	Pressing technique	HRB			
		1250 °C		1300 °C	
		C% as-sint	HRB	C% as-sint	HRB
1	CC	0.36	96	0.36	98
2	CC	0.44	98	0.45	100

Rockwell hardness HRC was measured on the materials cooled at 2-3 °C/s and on material 5 and 6, warm compacted, with 0.5 and 0.6% graphite after sintering at 1250 and 1300 °C and cooling at 0.5-1 °C/s.

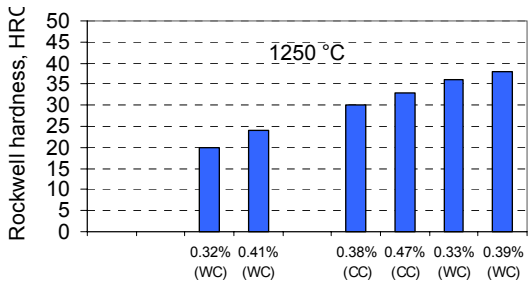


Figure 4. Hardness HRC. Cooling 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right).

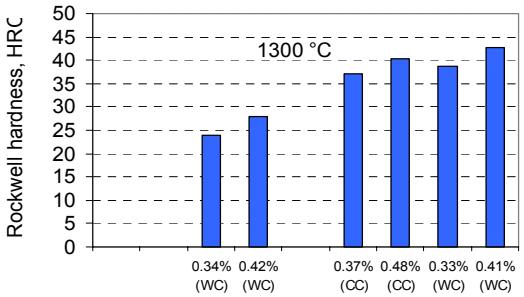


Figure 5. Hardness HRC. Cooling at 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right).

When the cooling rate is increased from 0.5-1 to 2-3°C/s, the hardness HV10 increases from 200-250 to 400-470 Vickers units depending on the carbon content and density. No major difference in hardness HV10 is observed when raising the sintering temperature from 1250 °C to 1300 °C at both cooling rates tested. When cooling at 2-3 °C/s, the Rockwell hardness obtained after sintering at 1300 °C is somewhat higher than when sintering at 1250 °C. Figures 6-13 present tensile and yield strength, elongation, transverse rupture strength and impact energy obtained after sintering at 1250 °C and 1300 °C and cooling at 0.5-1 and 2-3 °C/s. Diagrams on the left refer to sintering at 1250 °C, while those on the right refers to sintering at 1300 °C.

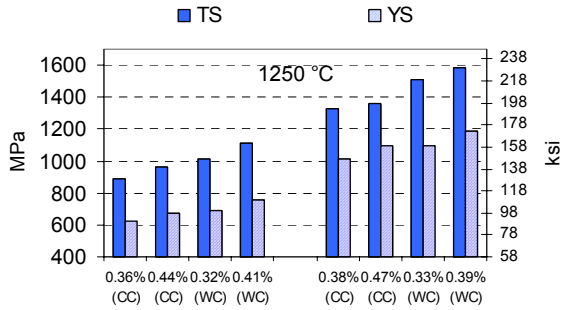


Figure 6. TS and YS. Cooling at 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right).

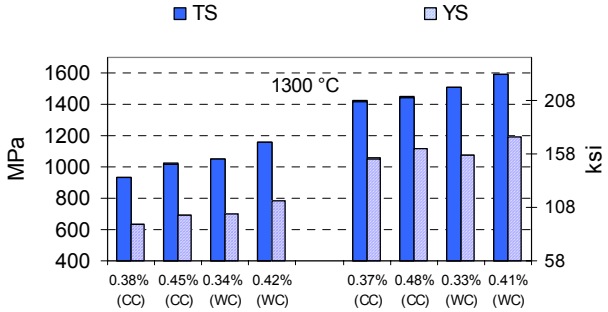


Figure 7. TS and YS. Cooling 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right).

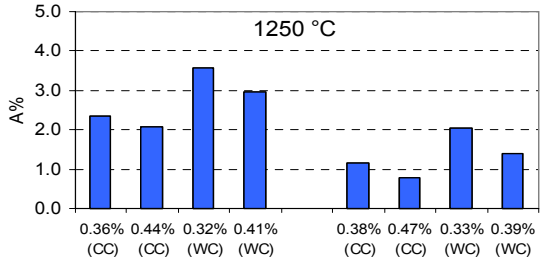


Figure 8. Elongation. Cooling at 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right).

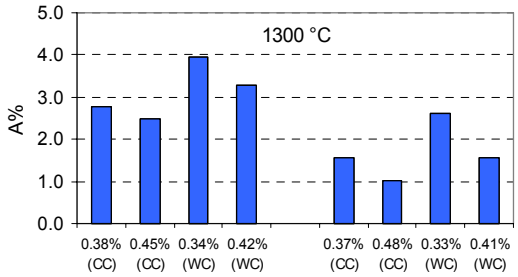


Figure 9. Elongation. Cooling at 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right).

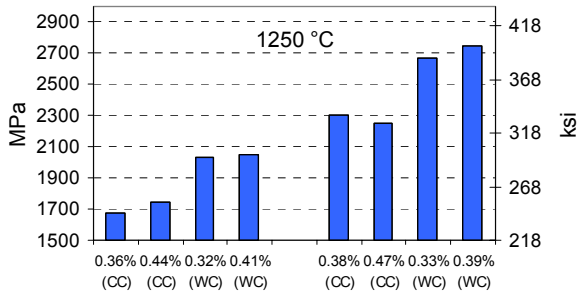


Figure 10. TRS. Cooling at 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right**).**

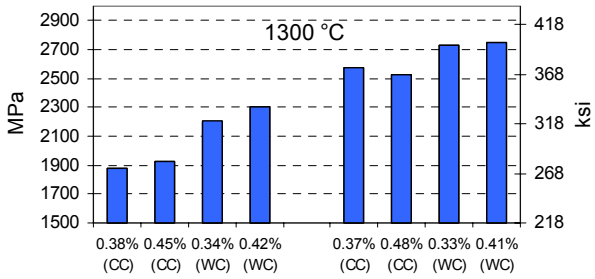


Figure 11. TR S. Cooling at 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right).

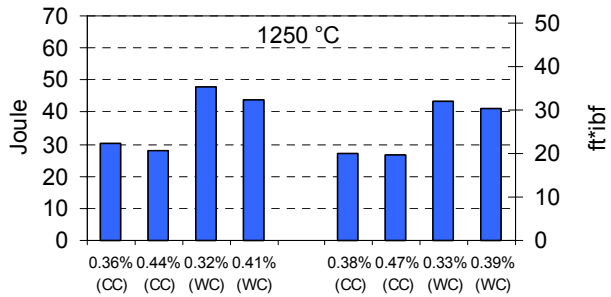


Figure 12. Impact energy. Cooling at 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right).

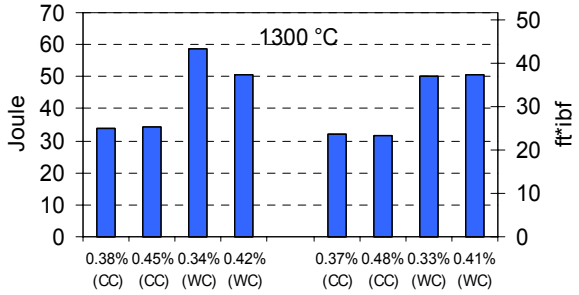


Figure 13. Impact energy. Cooling at 0.5-1 °C/s (bars on the left) and 2-3 °C/s (bars on the right).

High temperature sintering of Astaloy CrM gives a good combination of strength and toughness at both cooling rates and carbon levels tested. If cold compaction and lowest cooling rate are used, a tensile strength between 900-1000 MPa is obtained, depending on carbon content and sintering temperature, combined with an elongation of 2-2.5% and an impact energy of approx. 30 J. If high temperature sintering is combined with warm compaction, both strength and toughness are further improved and a tensile strength of 1100 MPa is achieved together with an elongation of 3% and an impact energy over 40 J.

By raising the cooling rate from 0.5-1 °C/s to 2-3 °C/s, independently of the sintering temperature, the tensile and yield strength are raised by around 50%. Elongation decreases, even though when cooling at 2-3 °C/s it achieves a level of 1-2.5%. Impact energy is similar or decreases slightly. At the highest cooling rate (1300 °C) a tensile strength of 1600 MPa is obtained combined with an elongation of 1.5% and impact energy of 50 J. By combining warm compaction with high temperature sintering strength and especially toughness reach very high values. By raising the sintering temperature from 1250 °C to 1300 °C, tensile strength is slightly raised, whereas no major improvement in yield strength is obtained. Impact energy is improved by 10-20% and elongation by 10-30%. This applies to both cooling rate tested.

Metallographic investigation was carried out on the tensile strength samples. Round pores and well-developed sintering necks were observed in all materials at both sintering temperatures tested. Fewer and smaller pores were obtained when combining high temperature sintering with warm compaction. Figures 14 and 15 gives an overview of the porosity for cold and warm compacted materials after sintering at 1250 °C.

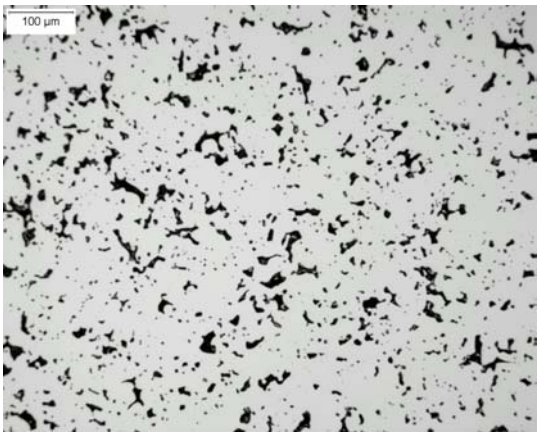


Figure 14. Astaloy CrM+0.5%C-UF4, cold compacted sintered at 1250 °C and cooled at 0.5-1 °C/s.

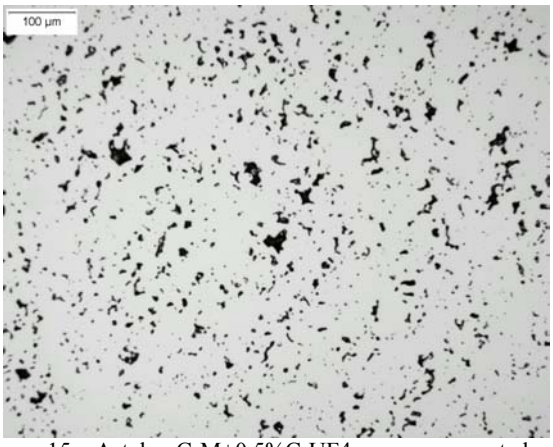


Figure 15. Astaloy CrM+0.5%C-UF4, warm compacted sintered at 1250 °C and cooled at 0.5-1 °C/s.

One tensile testing sample for each material was investigated with respect to microstructure. The microstructure consisted of bainite and martensite in different amounts depending on carbon content, cooling rate and density. The amount of martensite (M) and bainite (B) analysed after sintering is summarised in Table VIII and IX.

Table VIII. Phase amount at 0.5-1 °C/s

Mix No.	**Pressing technique**	**Phase amount %**					
		1250 °C			**1300 °C**		
		As-sint C%	**M%**	**B%**	**As-sint C%**	**M%**	**B%**
1	CC	0.36	1	99	0.38	3	97
2	CC	0.43	10	90	0.45	20	80
5	WC	0.32	1	99	0.34	1	99
6	WC	0.41	20	80	0.42	25	75

Table IX. Phase amount at 2-3 °C/s

Mix No.	**Pressing technique**	**Phase amount %**					
		1250 °C			**1300 °C**		
		As-sint C%	**M%**	**B%**	**As-sint C%**	**M%**	**B%**
1	CC	0.38	99	<1	0.37	99	1
2	CC	0.47	100		0.48	100	
5	WC	0.33	99	1	0.33	90	10
6	WC	0.39	100		0.41	100	

As an example figure 16 show the microstructure of Astaloy CrM with 0.6% graphite, cold compacted, after sintering at 1250 °C and cooling at 0.5-1 °C/s, while figure 17 show the microstructure of the same material after cooling at 2-3 °C/s.

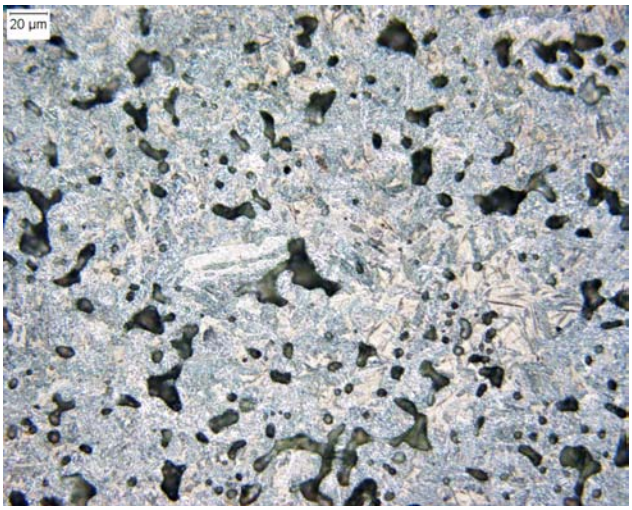


Figure 16. Astaloy CrM+0.6%C-UF4, cold compacted, sintering at 1250 °C and cooling at 0.5-1 °C/s. Bainite with approx. 10% of martensite.

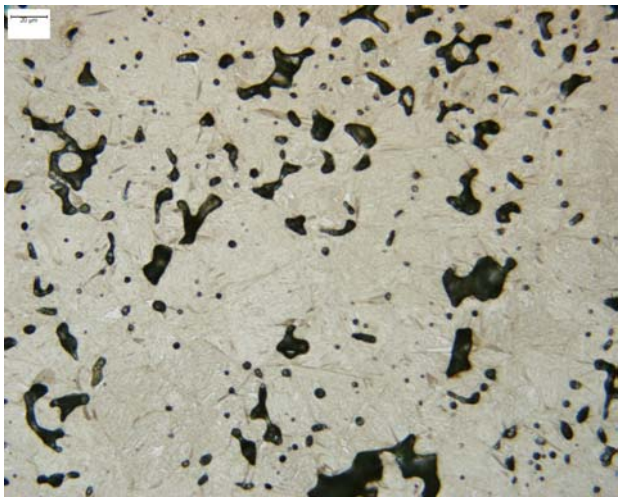


Figure 17. Astaloy CrM+0.6%C-UF4, cold compacted, sintering at 1250 °C and cooling at 0.5-1 °C/s. Martensite.

High temperature sintering combined with vacuum carburising

Carburising is carried out in order to introduce compressive stresses at the surface of a component. Compressive stresses contribute to an improved fatigue performance. Four points plane bending fatigue tests were carried out with load ratio R = -1, frequency 25 Hz, run out at 2 millions cycles. Fatigue limit [$\sigma_{A,50\%}$], (50% estimated survival value) and standard deviation, determined with stair case method, are evaluated according to MPIF Standard No.56, 2001. The results obtained for material 4 when high temperature sintered and than vacuum carburised are summarised in Table X. The S-N curve is shown in figure 18.

Table X. Properties of vacuum carburised Astaloy CrM

Material		C as-sint %	O as-sint %	SD g/cm^3	HV10	HRC	Fatigue strength MPa/ksi	
Mix No.	C-UF4 wt%						Mean	St. dev.
4	0.5	0.30	0.02	7.29	507	42	527 /76.7	<5/0.4

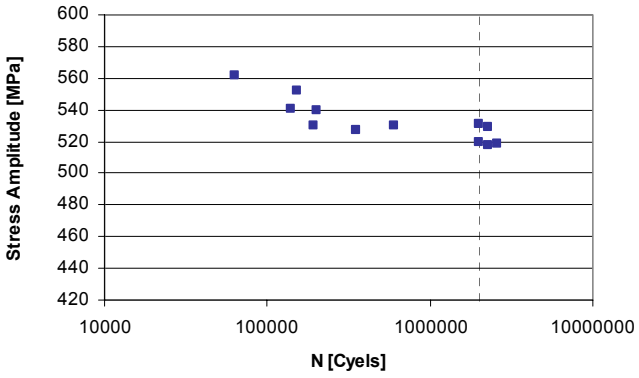


Figure 18. Fatigue strength after vacuum sintering combined with carburising.

Metallographic investigation carried out on the fatigue strength samples showed a martensitic structure at the surface, see figure 19. Some retained austenite and few carbides were also observed at the

surface. Mainly bainite with some martensite were found in the centre of the samples. Microhardness HV0.1 was measured. The profile is reported in figure 20.

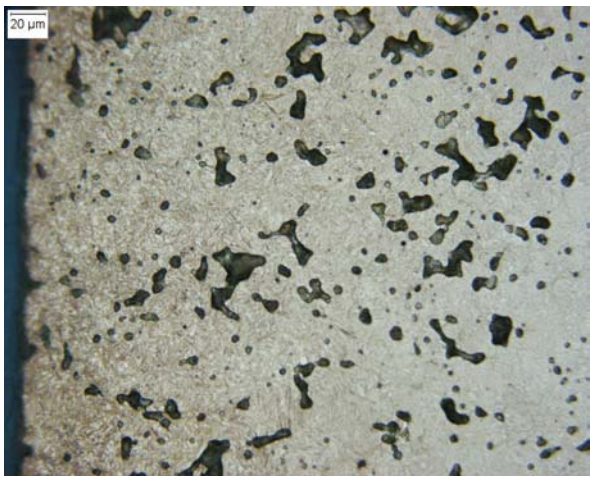


Figure 19. Surface. Martensite can be observed.

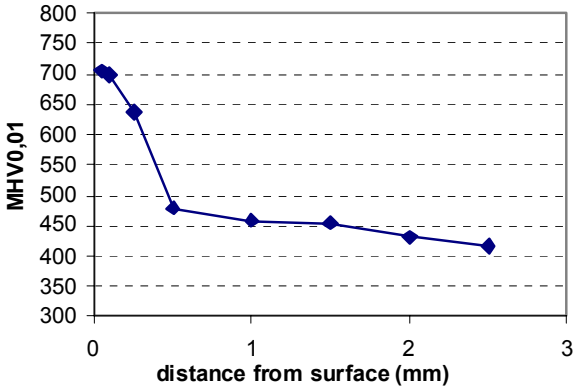


Figure 20. Microhardness profile.

Case hardening depth defined as the distance from the surface at which HV0.1 is below 550 Vickers units is approx. 0.4 mm.

Evaluation of dimensional stability in production environment

The outer diameter (OD) dimensions of 50 gears were measured in two directions perpendicular from each other on each set of sintering conditions. These dimensions were then used to analyse the dimensional change (die to as-sintered). The averages of these values can be seen in Table XI.

Table XI. Dimensional change and roundness on production gears

	Varicool on		Varicool off	
Property	**0°**	**90°**	**0°**	**90°**
Avg DC (%)	0.277	0.269	0.228	0.224
Std Dev (1 σ) DC (%)	0.051	0.050	0.020	0.018

Figure 21 shows the average dimensional change measured from die to as-sintered and the standard deviation (1σ).

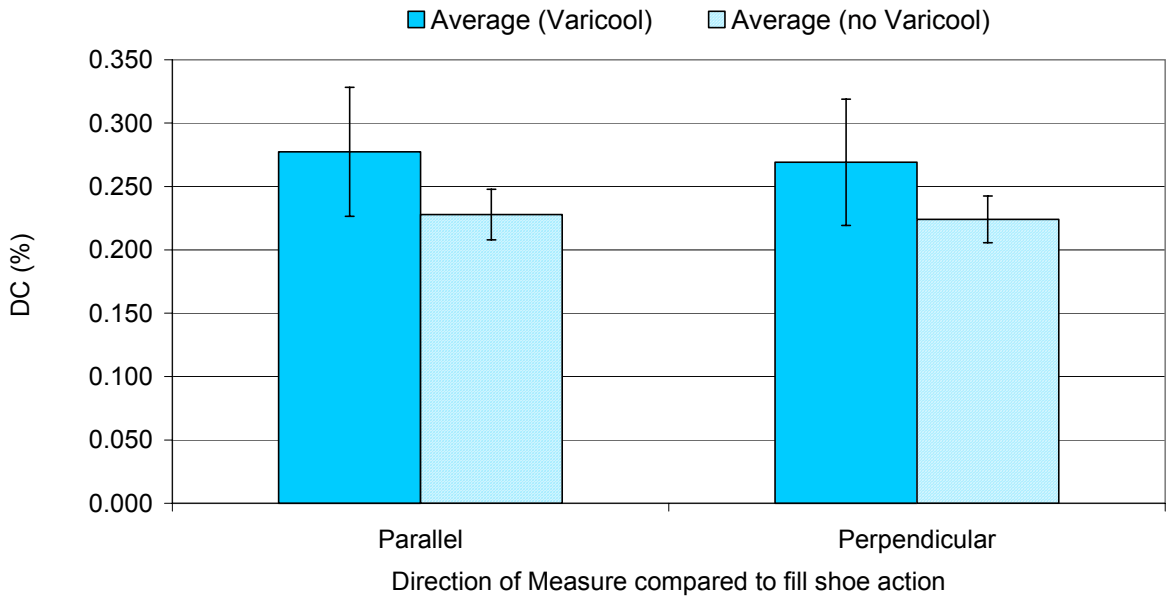


Figure 21: Dimensional change (die to as-sintered) and st. deviation (1 σ) measured with and without rapid cooling

Less shrinkage and slightly larger scatter in dimensional change was observed for the rapid cooled parts.

DISCUSSION

Raising the sintering temperature from 1120 to over 1200 °C is beneficial both for the strength and toughness of Astaloy CrM. As the alloying elements chromium and molybdenum are prealloyed to the iron the reason for the higher mechanical properties obtained after high temperature sintering, if as-sintered carbon content, sintered density and cooling rate are kept constant, is the formation of more developed sintering necks between the powder particles. This is due to the increased diffusion rate of iron, chromium and molybdenum, which results in higher density and, rounder and smaller pores.

A carbon loss between 0.1-0.2% is common during high temperature sintering of Astaloy CrM, due to reaction of the carbon with the oxygen in the powder and the surrounding atmosphere. Carbon loss depends on the oxygen content in the powder and on the sintering conditions e.g. atmosphere, temperature and furnace used. According to thermodynamics, the higher the sintering temperature, the higher the maximum partial pressure of oxygen that can be allowed in the sintering atmosphere, and therefore the smaller the risk for oxidation of chromium [3]. Very low oxygen content is normally obtained after sintering at temperature >1200 °C. In this investigation an oxygen content <0.02% was analysed on all samples.

For high-strength applications a microstructure consisting of bainite and/or martensite is desired. Normally, the strength and hardness of a material is enhanced if the martensite/bainite ratio is increased. By raising the cooling rate from 0.5-1 to 2-3 °C/s, the microstructure of the investigated materials was transformed from a mixture of bainite with some martensite (max 25%) to an almost entirely martensitic structure. The increase in martensite content is responsible for the high strength and hardness obtained after cooling at 2-3 °C. The advantage of high temperature sintering materials based on Astaloy CrM is that high strength is combined with high levels of elongation and impact energy. A tensile strength of 1600 MPa is achieved in combination with 1.5% elongation and impact energy of 50 J.

Impact energy and elongation are the properties that most benefit from an increase in sintering temperature from 1250 to 1300 °C and from combining high temperature sintering with warm compaction. In fact, both an increase in sintering temperature from 1250 to 1300 °C and the use of warm compaction in combination with high temperature sintering mainly results in increased density.

A slightly higher martensite content was found in the warm compacted samples, despite the similar or somewhat lower as-sintered carbon content. The reason for this could be the higher sintered density obtained for the warm compacted materials, which improves hardenability. A higher amount of bainite (10%) was found in the warm compacted material with 0.33% as-sintered carbon (0.5% admixed graphite) sintered at 1300 °C and rapidly cooled, compared to the corresponding material sintered at 1250 °C. This indicates that Astaloy CrM with 0.3-035% undergoes a transition between bainite and martensite when cooled at 2-3 °C/s. Small variations in cooling rate, carbon content and density results in different amounts of martensite and bainite which can lead to increased scatter in mechanical properties. An as-sintered carbon content between 0.4-0.45% is recommended to achieve an entirely martensitic structure, when cooling at 2-3 °C/s.

Many components, gears for example, require a hard surface and a tough core. These properties are commonly achieved by case hardening operations such as carburising. In order to eliminate the risk of oxidation, the possibility of combining high temperature sintering with carburising in vacuum was investigated. The advantage of this process is that sintering and the heat treatment operation are carried out in one step. Even though the heat treatment conditions were not fully optimised, a fatigue limit of 527 MPa was obtained. A thin martensite layer was obtained at the surface followed by bainite. Few carbides and some retained austenite were found, especially in the corners of the components, indicating that the carbon content at the surface should be decreased. Moreover, the case depth obtained was too shallow; requested case depth is normally 0.5-0.8 mm. More work is needed in order to optimise this type of heat treatment for PM components.

Dimensional stability is one of the most important properties to be studied in production. New alloys that are used to improve strength and mechanical properties must also maintain or improve on the dimensional stability of materials previously used in PM. Process conditions, pressing and sintering were not optimised for Astaloy CrM during production tests. However, Astaloy CrM has shown to maintain good dimensional stability under normal cooling conditions. Slightly larger scatter was obtained when rapid cooling was used.

CONCLUSIONS

High temperature sintered Astaloy CrM, with a combined carbon content of 0.3-0.45%, gives a unique combination of strength and toughness, both when cooled at 0.5-1 °C/s and 2-3 °C/s.

A tensile strength of 1020 MPa combined with an elongation of 2.5% and impact energy of 34 J is achieved by Astaloy CrM with 0.4% carbon and density 7.1 g/cm^3 when high temperature sintered and cooled at 0.5-1 °C/s.

Strength is increased when combining high temperature sintering with rapid cooling. A tensile strength of 1450 MPa, elongation of 1% and impact energy of 32 J is obtained by Astaloy CrM with 0.4% carbon and sintered density of 7.1 g/cm^3 when cooled at 2-3 °C/s.

By combining warm compaction with high temperature sintering followed by cooling at 2-3 °C/s Astaloy CrM achieves a tensile strength of 1600 MPa together with an elongation of 1.5% and impact energy of 50 J.

When increasing the sintering temperature from 1250 to 1300 °C, toughness of Astaloy CrM based materials is improved, while no major improvement in yield and tensile strength is obtained either when cooling at 0.5-1 °C/s or 2-3 °C/s.

Warm compaction combined with high temperature sintering improves both impact energy and elongation by more than 40%, while tensile and yield strength are improved by 10-20%.

Warm compaction combined with high temperature sintering and vacuum carburising of Astaloy CrM with 0.3%C and a density of 7.3 g/cm^3 gives a plane bending fatigue strength of 527 MPa.

When processing Astaloy CrM-based gears, under production conditions, good dimensional stability is achieved with normal cooling conditions. Dimensional stability decreases only slightly when rapid cooling is used.

REFERENCES

[1] U. Engström, J. McLelland, B. Maroli, "Effect of sinter-hardening on the properties of high temperature sintered PM steels", *Advances in Powder metallurgy & Particulate Materials*, 2002, p 13-1 to 13-15

[2] A. Bergmark, L. Alzati, U. Persson, "Fatigue Crack Initiation in PM Steel", *Advances in Powder metallurgy & Particulate Materials*, 2002, p 5-95 to 5-103 [2] B.

[3] B. Lindqvist, K. Kanno, "Considerations when sintering oxidation sensitive PM steels" *Advances in Powder metallurgy & Particulate Materials*, 2002

[4] U. Engström, "Influence of sintering temperature on properties of low alloyed high strength PM materials", *Advances in Powder metallurgy & Particulate Materials*, 2001

[5] U. Engström, "Evaluation of sinter-hardening of different PM materials", *Advances in Powder metallurgy & Particulate Materials*, 2000, p 5-147 to 5-157