EFFECT OF SINTER-HARDENING ON THE PROPERTIES OF HIGH TEMPERATURE SINTERED PM STEELS

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ABSTRACT

The development of new materials and cost-effective processes are two factors that have contributed to the strong growth of PM parts over the past decades. Sinter-hardening is one example of such development combining 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 controlled to form the required amount of martensite to obtain the desired mechanical properties. By increasing the sintering temperature from 1120ºC (2048ºF) to 1250ºC (2282ºF) these properties can be further increased.

In this paper sinter-hardening of a number of PM materials is presented. The influence of alloying system, sintering temperature and cooling rate on both microstructure and mechanical properties will be discussed.

INTRODUCTION

Microstructure control by proper selection of the material and processing conditions offers opportunities to improve mechanical performance. For high strength applications a microstructure consisting of bainite and martensite is desired. The martensite to bainite ratio is depending on the properties to be achieved.

Changing the type and amount of alloying elements, the post-sintering cooling rate and the sintering temperature, can vary the quantity of martensite and bainite in the microstructure. Powder grades pre-alloyed with molybdenum, nickel and chromium are used to achieve a bainitic/martensitic structure after sintering. Copper and nickel are added to the base powder to improve its hardenability. By accelerating the post sintering cooling rate the quantity of martensite can be increased which results in increased strength and hardness. Rising the sintering temperature from 1120 °C (2048 °F) to 1250 °C (2282 °F) results in higher densities, rounder pores as well as larger inter pore spacing. In the case of a fully pre-alloyed material admixed with graphite no major changes in microstructure take place when increasing the sintering temperature, if the cooling rate is kept constant. If the base powder is admixed

with copper and nickel increased sintering temperature leads to a more even distribution of alloying elements and as a consequence increased hardenability of the base powder. By combining high temperature sintering with an accelerated post-sintering cooling rate performance of PM materials can be further improved. The quantity of martensite is increased this combined with higher density and smoother porosity.

The larger the amount of martensite, the higher the hardness. High hardness makes sizing operation to correct dimensions very difficult. Therefore, small scatter in dimensional change is a must for sinter-hardened materials. Tighter dimensional tolerances can be achieved if a pre-alloyed powder is used and additions of copper can be avoided.

The aims of this study are: a) to investigate the influence of the sintering temperature and cooling rate on the mechanical properties of four different PM-materials; b) to study the dimensional scatter of two pre-alloyed materials, one admixed with copper and one without copper additions, after sintering at 1120 °C (2048 °F) and 1250 °C (2282 °F).

MATERIALS

Five materials were investigated based on Astaloy A, Astaloy Mo and Astaloy CrM. The chemical composition of the base powders used is reported in Table I. Chemical composition of the studied materials is reported in Table II.

Table I: Chemical composition of the investigated base powders.

Grade	**Ni %**	**Mo %**	**Cr %**	**Mn %**
Astaloy A	1.9	0.5		0.2
Astaloy CrM		0.5	3.0	
Astaloy Mo		1.5		0.1

Table II: Chemical composition of the investigated materials

Material nr	**Grade**	**Cu wt %**	**Ni wt%**	**Graphite wt%**	**A-wax wt%**
1	Astaloy A	2		0.8	0.8
2	Astaloy CrM			0.55	0.8
3	Astaloy CrM			0.6	0.8
4	Astaloy Mo		2	0.8	0.8
5	Astaloy Mo	2		0.8	0.8

Kropmülf graphite UF4% (96-97 % C), copper –165 µm and Ni type Inco 123 were admixed with the base powder. Amide wax was used as lubricant.

Two Astaloy CrM mixes were prepared in order to achieve the same carbon content after sintering at 1120 °C (2048 °F) and 1250 °C (2282 °F).

PROCESSING CONDITIONS

Evaluation of sintered properties

The materials in table II were pressed to achieve a green density of 6.9 g/cm^3 and at a constant pressure of 800 MPa (58 tsi). Pressing was carried out in a Result semiautomatic laboratory press. The following samples geometries were pressed: tensile testing samples (ISO 2470-1986), impact energy samples (ISO 3325) and transverse rupture strength samples (ISO 5754).

Four sintering conditions were tested, as summarised in Table III. Sintering at 1120 °C (2048 °F) was carried in two different laboratory mesh belt furnaces, one equipped with a rapid cooling unit (test 2) and one not (test 1). Sintering at 1250 °C (2282 °F) was carried out in a lifting earth furnace equipped with a unit for rapid cooling. 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**
Material	1,2,4,5	1,2,4,5	1,3,4,5	1,3,4,5
Temperature	1120 °C/2048 °F	1120 °C/2048 °F	1250 °C/ 2282 °F	1250°C/ 2282 °F
Time	30 min	30 min	30 min	30 min
Cooling rate	0.25-0.8 °C/s 0.45-1.4 °F/s	2-3 °C/s 3.6-5.4 °F/s	0.25-0.8 °C/s 0.45-1.4°F/s	2-3 °C/s 3.6-5.4 °F/s
Atmosphere	90-10 N_2-H_2+CH_4	90-10 N_2-H_2	90-10 N_2-H_2	90-10 N_2-H_2

Cooling rate was determined by comparing the microstructure of the investigated materials with CCT diagrams [1].

Evaluation of dimensional scatter

The dimensional scatter of Astaloy A with copper and graphite additions and Astaloy CrM with graphite additions was investigated. At this purpose the following processing route was chosen.
A total of 1500 gears of materials 1,2,3 were pressed at 650 MPa (47 tsi) to achieve a green density of about 6.9 g/cm^3. The pressed gears had an outer diameter of 22 mm (0.8668 inch), inner diameter of 8 mm (0.3152 inch) and height of 11 mm (0.4334 inch). See Fig 1. Materials 1 and 2 were sintered at 1120 °C (2048 °F) for 30 min in 90-10 N_2-H_2 with CH_4 additions in a mesh belt laboratory furnace. The gears were placed in trays. Thirty gears were placed in each tray. Five gears were sampled from each tray and measured. Materials 1 and 3 were sintered at 1250 °C (2282°F) for 70 min in N_2-H_2 atmosphere in a continuous production furnace. Cooling rate was 0.25-0.8 °C/s (0.45-1.4 °F/s). The samples were placed in trays as shown in Figure 2. Five gears were placed around each peg and 120 gears were located in each tray. Three groups of five samples were collected from each tray and measured after sintering. A total of 150 samples for each material and sintering condition were measured in green and sintered state. Inner and outer diameter, as well as base tangent length (see Figure 1), was measured by using a micrometer. All measured gears were marked in order to identify their location in the sintering trays and the sintering sequence.

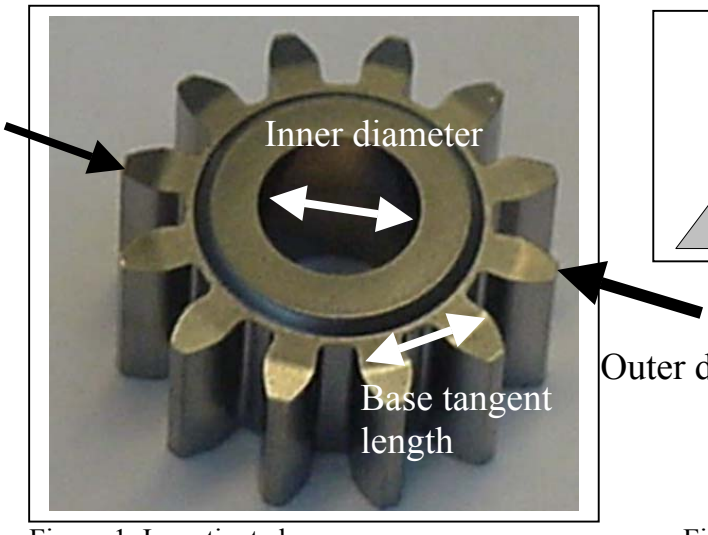


Figure 1. Investigated gear

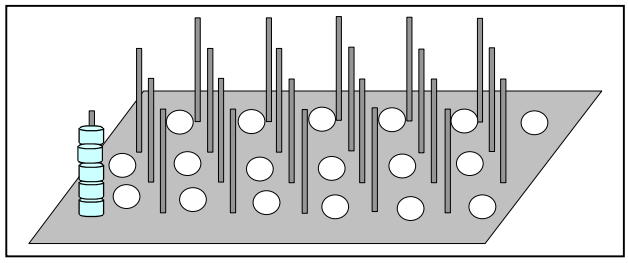


Figure 2. Tray used for sintering at 1250 °C

RESULTS

Evaluation of sintered properties

Density, dimensional change, tensile and yield strength, elongation, transverse rupture strength, impact energy, hardness and microstructure were evaluated. The investigated materials have different compressibility; therefore they show different green densities after compaction at 800 MPa. The results are summarised in Table IV.

Table IV. Green density after compaction at 800 MPa

Material	**GD(g/cm^3)**
A A+2%Cu+0.8%C-UF+0.8% H-wax	7.08
A CrM+0.55%C-UF+0.8%H-wax	7.03
A CrM+0.59%C-UF+0.8%H-wax	7.03
A Mo+2%Ni+0.8%C-UF+0.8%H-wax	7.13
A Mo+2%Cu+0.8%C-UF+0.8%H-wax	7.15

Cooling at 0.25-0.8 °C/s

Density obtained after cooling at 0.25-0.8 °C/s is reported in Figure 3. The Astaloy Mo materials show highest compressibility due to the lower amount of alloying elements in the base powder.

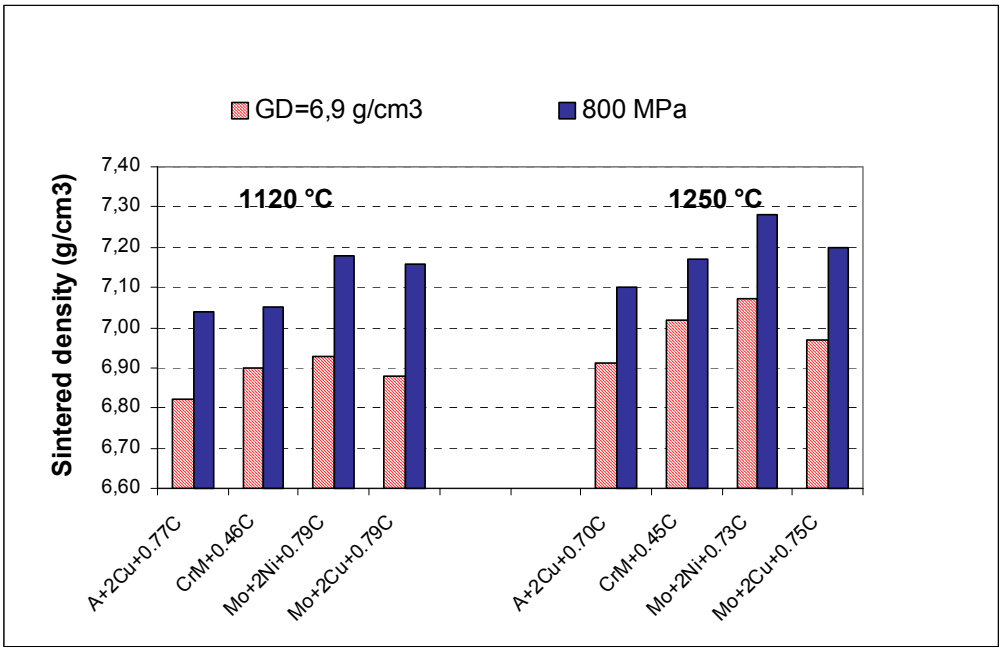


Figure 3. Influence of sintering temperature on density. Cooling rate 0.25-0.8 °C/s

Astaloy CrM shows higher density compared to Astaloy A at both sintering temperatures, even though the green density is lower. Astaloy Mo with copper additions has lower sintered density, if compared to the material based on Astaloy Mo with Ni additions. This is due to the swelling effect caused by copper.

Hardness measured after sintering at 1120 °C and 1250°C and cooling at 0.25-0.8 °C/s is reported in Figure 4. Rockwell B hardness was measured except for the Astaloy A and Astaloy CrM materials sintered at 1120 °C and for the Astaloy CrM material compacted at 800 MPa and sintered at 1250 °C. For these materials Rockwell C was used. When sintering at 1120 °C, higher hardness is observed for

the Astaloy A and Astaloy CrM materials. When sintering at 1250 °C the Astaloy CrM material obtains slightly higher hardness. When increasing the sintering temperature, hardness decreases slightly for the Astaloy A, Astaloy CrM and Astaloy Mo material with copper additions. Hardness of the Astaloy Mo material with Ni additions increases slightly. The reason for this can be found in the microstructure.

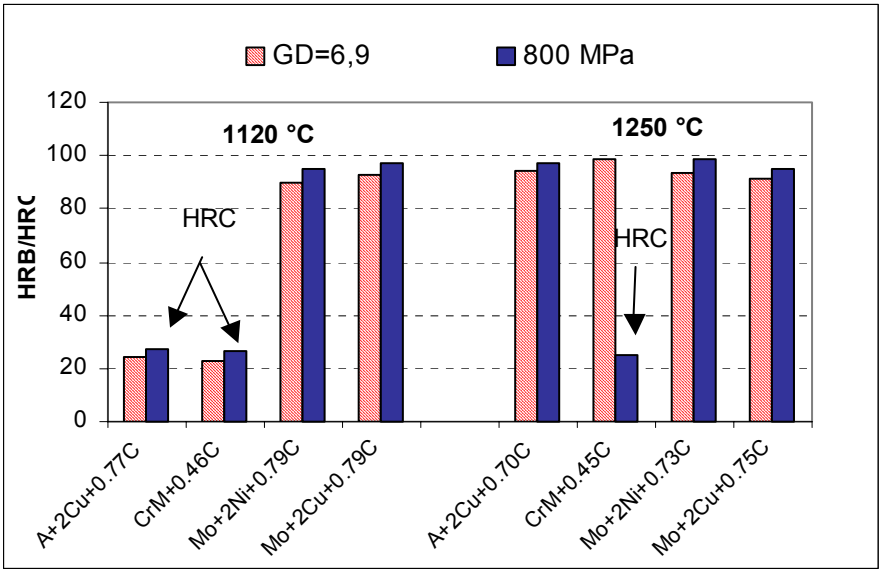


Figure 4. Influence of sintering temperature on hardness. Cooling 0.25-0.8°C/s

Mechanical properties after sintering at 1120 °C and 1250 °C and cooling at 0.25-0.8 °C/s are reported in Table V.

Table V. Mechanical properties after cooling at 0.25-0.8 °C/s

	C	TS		YS		A		IE		TRS	
	as-sint	**6.9 g/cm3**	**800 MPa**	**6.9 g/cm3**	**800 MPa**	**6.9 g/cm3**	**800 MPa**	**6.9 g/cm3**	**800 MPa**	**6.9 g/cm3**	**800 MPa**
	Wt %	**MPa(ksi)**	**MPa(ksi)**	**MPa(ksi)**	**MPa(ksi)**	%	%	**J (ft-lb)**	**J (ft-lb)**	**MPa(ksi)**	**MPa(ksi)**
1120 °C											
A A+2Cu	0.77	794(115)	886(128)	621(90)	688(100)	0.7	0.8	13(10)	17(13)	1258(182)	1514(220)
A CrM	0.46	872(126)	953(138)	663(96)	713(103)	0.9	1.0	15(11)	19(14)	1496(217)	1650(239)
A Mo+2Ni	0.79	673(98)	790(115)	508(74)	578(84)	1.1	1.6	14(10)	20(15)	1224(177)	1460(212)
A Mo+2Cu	0.79	707(103)	841(122)	545(79)	631(91)	1.0	1.4	13(10)	19(14)	1218(177)	1509(219)
1250 °C											
A A+2Cu	0.70	777(113)	835(121)	579(84)	628(91)	1.3	1.3	17(13)	24(18)	1339(194)	1552(225)
A CrM	0.45	985(143)	1087(158)	686(99)	757(110)	1.9	2.1	23(17)	34(25)	1816(236)	1964(285)
A Mo+2Ni	0.73	751(109)	868(126)	561(81)	630(91)	1.6	2.2	23(17)	33(24)	1456(211)	1662(241)
A Mo+2Cu	0.75	721(105)	780(113)	554(80)	602(87)	1.5	1.5	16(12)	25(18)	1300(189)	1541(223)

Astaloy CrM shows highest tensile, yield and transverse rupture strength both at 1120 °C and 1250 °C at both density levels tested. Astaloy CrM shows highest impact energy except when sintering at 1120 °C and compacting at 800 MPa. In this case the Astaloy Mo material with nickel additions shows highest impact energy. When sintering at 1250 °C, Astaloy CrM has highest tensile and yield strength in combination with an elongation of approx. 2.0%.

Tensile and yield strength increase with rising sintering temperature for the Astaloy CrM and the Astaloy Mo material with nickel additions. The tensile and yield strength of the Astaloy A material decreases with increasing sintering temperature. The tensile and yield strength of Astaloy Mo material with Cu additions is similar or decreases when the sintering temperature goes up. Impact energy and

transverse rupture strength increase with increased sintering temperature for all materials. However, the largest improvement is observed for the Astaloy CrM and Astaloy Mo material with nickel additions.

The microstructure of the investigated materials was studied. The results obtained when cooling at 0.25-0.8 °C/s are summarised in Table VI. The results are representative for both density levels studied. Martensite content decreases with increased sintering temperature for the Astaloy A and Astaloy Mo materials. Some retained austenite was observed between the martensite needles in the Astaloy A and Astaloy Mo materials with copper additions.

Table VI: Phase analysis for dT/dt 0.25-0.8 °C/s

	C% as-sint	**M %**	**M+A %**	**B %**
1120 °C				
A A+2%Cu	0.79	35%		Bal.
A CrM	0.46	10-15%		Bal.
A Mo+2%Ni	0.79		10%	Bal.
A Mo+2%Cu	0.79	5%		Bal.
1250 °C				
A A+2%Cu	0.70	5%		Bal.
A CrM	0.45	5%		Bal.
A Mo+2%Ni	0.73		5%	Bal.
A Mo+2%Cu	0.75	<1%		Bal.

Cooling at 2-3 °C/s

In addition to cooling at 0.25-0.8 °C/s, all materials were also cooled at 2-3 °C/s. Sintered densities after cooling follow the same trends as for the 0.25-0.8 °C/s cooling rate.

Hardness was measured after sintering at both 1120 °C and 1250 °C with the 2-3 °C/s cooling rate. These results can be seen is Figure 5. All hardness values are reported in HRC. Higher hardness is seen as sintering temperature increases. Astaloy CrM as well as the Astaloy Mo materials sees very good improvement in hardness with increasing sintering temperature regardless of density. Astaloy A does not improve as greatly as the others do. Increasing the cooling rate from 0.25-0.8 °C/s to 2-3 °C/s gives excellent improvement in hardness.

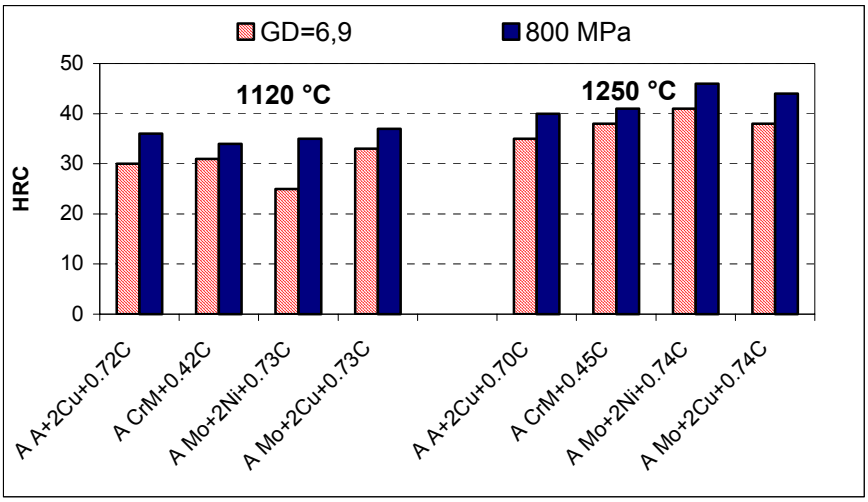


Figure 5. Influence of sintering temperature on hardness. Cooling 2-3 °C/s

Mechanical properties for sintering at both 1120 °C and 1250 °C with the cooling rate of 2-3 °C/s are shown in Table VII. Similar to the slower cooling rate already discussed, Astaloy CrM demonstrates the highest tensile and yield strength at both 1120 °C and 1250° C. Astaloy CrM exhibits the highest transverse rupture strength as well, except when sintering at 1120 °C at a compaction force of 800 MPa. Impact energy is also greatly improved for Astaloy CrM as the sintering temperature is raised. At 1120 °C, Astaloy Mo with nickel additions has the highest elongation. At 1250 °C, Astaloy CrM has the highest elongation and impact energy.

Tensile, yield, and transverse rupture strength as well as elongation and impact energy increase for all materials with respect to increasing sintering temperature.

Table VII: Mechanical properties after cooling at 2-3 °C/s

	C	TS		YS		A		IE		TRS	
	As-sint	6.9 g/cm3	800 MPa	6.9 g/cm3	800 MPa	6.9 g/cm3	800 MPa	6.9 g/cm3	800 MPa	6.9 g/cm3	800 MPa
	Wt%	MPa(ksi)	MPa(ksi)	MPa(ksi)	MPa(ksi)	%	%	J(ft-lb)	J(ft-lb)	MPa(ksi)	MPa(ksi)
1120 °C											
A A+2Cu	0.72	838(122)	969(141)	718(104)	788(114)	0.4	0.3	14(10)	18(14)	1493(217)	1699(246)
A CrM	0.42	1032(150)	1144(166)	913(132)	982(142)	0.4	0.4	14(10)	16(12)	1635(237)	1818(264)
A Mo+2Ni	0.73	790(115)	965(140)	670(97)	795(115)	0.4	0.7	13(9)	20(14)	1466(213)	1788(259)
A Mo+2Cu	0.73	925(134)	1137(165)	820(119)	941(137)	0.4	0.6	15(11)	23(17)	1634(237)	2010(292)
1250 °C											
A A+2Cu	0.70	957(139)	1109(161)	780(113)	875(127)	0.5	0.6	23(17)	28(21)	1518(220)	1751(254)
A CrM	0.45	1290(187)	1421(206)	1014(147)	1095(159)	0.9	1.1	29(21)	38(28)	2118(307)	2433(353)
A Mo+2Ni	0.74	1090(158)	1307(190)	854(124)	961(139)	0.5	0.6	25(18)	31(23)	1880(273)	2113(306)
A Mo+2Cu	0.74	1072(156)	1318(191)	902(131)	1034(150)	0.5	0.6	21(15)	35(26)	1753(254)	2060(299)

Table VIII shows the phase analysis for the microstructures of all the materials cooled at 2-3 °C/s. No major differences were seen in the microstructures with respect to density. Astaloy A and Astaloy CrM forms almost 100% martensite at both sintering temperatures whereas for the Astaloy Mo materials with nickel and copper additions the quantity of martensite increases with increasing sintering temperature. Some retained austenite was observed between the martensite needles in the Astaloy and Astaloy Mo materials with copper additions.

TableVIII: Phase analysis for cooling rate 2-3 °C/s

	C%	M%	M+A%	B%
1120 °C				
Ast A+2%Cu	0.72	Bal.		1%
Ast CrM	0.42	Bal.		3-5%
Ast Mo+2%Ni	0.73		Bal.	15-25%
Ast Mo+2%Cu	0.73	Bal.		15-30%
1250 °C				
Ast A+2%Cu	0.70	Bal.		
Ast CrM	0.45	Bal.		<1%
Ast Mo+2%Ni	0.74		Bal.	1-2%
Ast Mo+2%Cu	0.74	Bal.		<1%

Tensile, yield, and transverse rupture strength increase with increasing cooling rate at both sintering temperature tested for all materials. The increase is not as dramatic for the Astaloy A material. Elongation decreases for all materials with increasing cooling rate. Impact energy is unchanged when sintering at 1120 °C, however differently from what expected it increases for all materials with increased cooling rate at the sintering temperature of 1250 °C.

Evaluation of dimensional scatter

The green samples were measured with respect to inner and outer diameter (Table IX). Sintered samples were measured with respect to inner and outer diameter as well as base tangent length (Table X). The results in Tables IX and X are based on 150 measurements for each material. Figures 6 a) and b) show the scatter in teeth distance after sintering at 1120 and 1250 °C.

Table IX. Average inner & outer diameter for green samples

Green dimensions	Inner diameter mm		Outer diameter mm	
	Mean	6σ	Mean	6σ
Astaloy A + 0.8%C-UF + 2%Cu	8.085	0.011	22.327	0.008
Astaloy CrM + 0.55%C-UF	8.085	0.011	22.327	0.006
Astaloy CrM + 0.59%C-UF	8.086	0.011	22.327	0.008

Table X. Average inner & outer diameter and base tangent length for sintered samples

1120 °C	C-as sintered wt%	Inner diameter mm		Outer diameter mm		Base tangent length mm	
		Mean	6σ	Mean	6σ	Mean	6σ
A A +2%Cu	0.75	8.101	0.019	22.379	0.021	7.296	0.019
A CrM	0.48	8.072	0.017	22.304	0.016	7.269	0.016

1250 °C	C-as sintered wt%	Inner diameter mm		Outer diameter mm		Base tangent length mm	
		Mean	6σ	Mean	6σ	Mean	6σ
A A + 2%Cu	0.71	8.073	0.025	22.314	0.039	7.272	0.034
A CrM	0.41	8.032	0.019	22.177	0.037	7.225	0.016

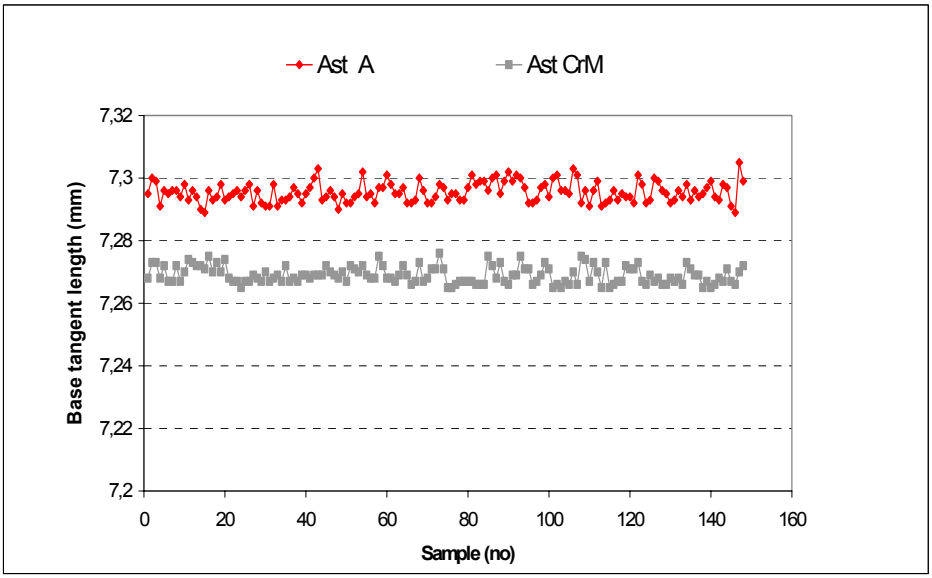


Figure 6a. Base tangent length, T=1120 °C

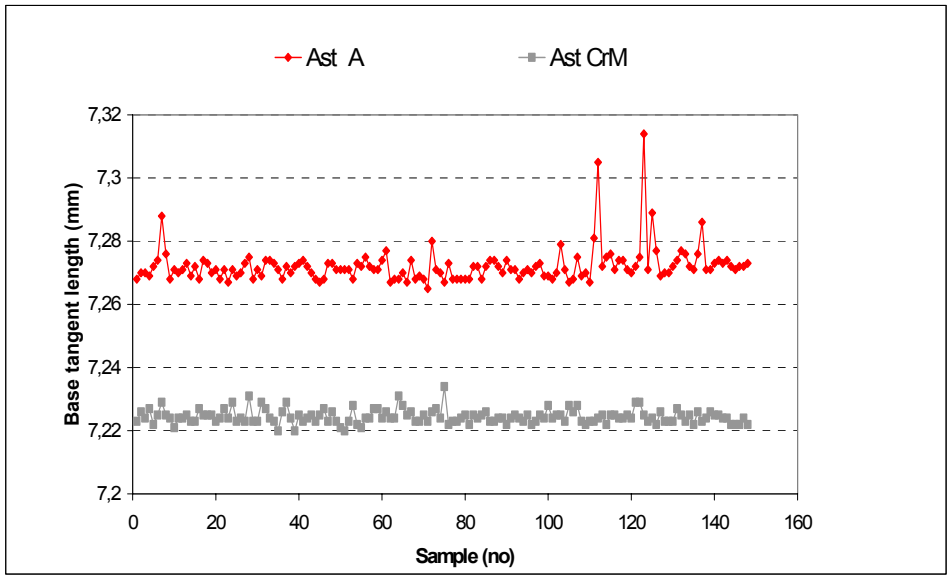


Figure 6b. Base tangent length, 1250 °C

No major differences neither in dimensions or scatter were observed between the Astaloy CrM and Astaloy A materials when measured in green conditions. In the as-sintered conditions Astaloy CrM has a narrower scatter for all measured dimensions, both at 1120 and at 1250 °C. The scatter of the Astaloy A material increases by more than 50% when increasing the sintering temperature. For the Astaloy CrM material the scatter in base tangent length is unchanged, while the scatter in inner diameter increases only slightly when the sintering temperature rises. Scatter in outer diameter increases.

DISCUSSION

An increase in sintering temperature from 1120 to 1250 °C and cooling at 0.25-0.8 °C/s has a beneficial effect on the mechanical properties of Astaloy CrM. High temperature sintering improves the sintering necks, promotes pore rounding and shrinkage. Tensile, yield, and transverse rupture strength as well as impact energy and elongation are improved. Hardness decreases slightly due the fact that the materials sintered at 1120 °C have larger amount of martensite. By considering the microstructure of Astaloy CrM after sintering at 1120 °C and 1250°C and cooling at 0.25-0.8 °C/s it can be concluded that the cooling rate of the furnaces used for sintering at 1120 °C was slightly higher, if compared to the high temperature sintering furnace. In fact a larger amount of martensite (see Table VI) was obtained after sintering at 1120 °C.

Hardness, tensile and yield strength decrease with increased sintering temperature for the Astaloy A and Astaloy Mo materials with copper additions. This is explained by the lower amount of martensite present after sintering at 1250 °C. The decrease in martensite content for the Astaloy Mo and Astaloy A materials can be explained by the lower cooling rate and lower carbon content obtained after high temperature sintering. Impact energy and transverse rupture strength of the Astaloy A and Astaloy Mo materials with copper increase modestly with increased sintering temperature. This increase is due to increased density combined with pore rounding. However, the increase in transverse rupture strength and impact energy is limited by the fact that martensite content decreases.

Tensile, yield, and transverse rupture strength as well as impact energy of the Astaloy Mo material with Ni additions increase even though the martensite content in the microstructure decreases. This can be explained by the fact that this material shows the largest improvement in sintered density. Improved strength can also be related to the reduced amount of austenite in the microstructure.

Increasing sintering temperature from 1120 °C to 1250 °C at the cooling rate of 2-3 °C/s yielded improved mechanical properties for Astaloy CrM as well as Astaloy Mo materials. However, it is interesting to note how elongation increases greatly for Astaloy CrM with increasing sintering temperature. Improved mechanical properties can be explained by the increasing martensite content for all of these materials (mostly for the Astaloy Mo materials), better sinter necks and pore roundness. This can be seen below as Astaloy CrM in Figure 7e (1250 °C, 2-3 °C/s) has much better pore roundness than the same material sintered at 1120 °C, 2-3 °C/s as shown in Figure 7b. All materials sintered at 1120 °C and cooled at 2-3 °C/s are shown below in Figures 7a-7d.

The amount of martensite in the Astaloy Mo with copper additions, as well as with nickel additions increases with raised sintering temperature at the cooling rate of 2-3 °C/s. The higher sintering temperature allow for better diffusion of alloying elements and therefore a better hardenability of the base powder.

Astaloy A does not have quite the improvement that the other materials when increasing sintering temperature. Almost 100% martensite is present at both 1120 °C and 1250 °C, 2-3 °C/s at both density levels.

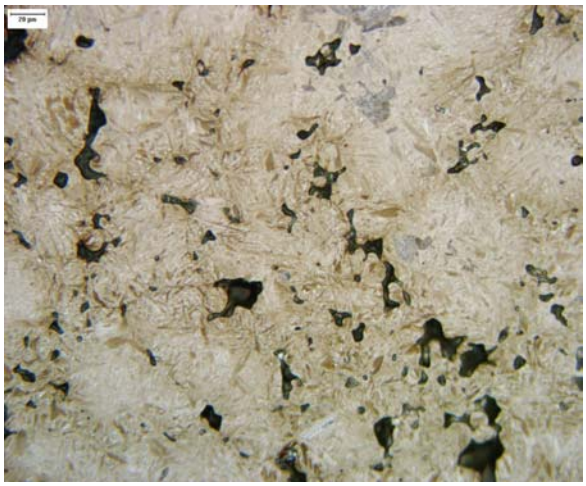


Figure 7a: Astaloy A + 2% Cu + 0.75% C
T=1120 °C dT/dt=2-3 °C/s

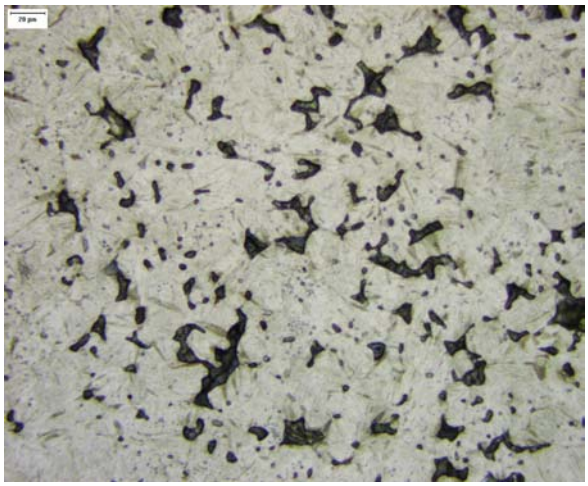


Figure 7b: Astaloy CrM + 0.45% C
T=1120 °C dT/dt=2-3 °C/s

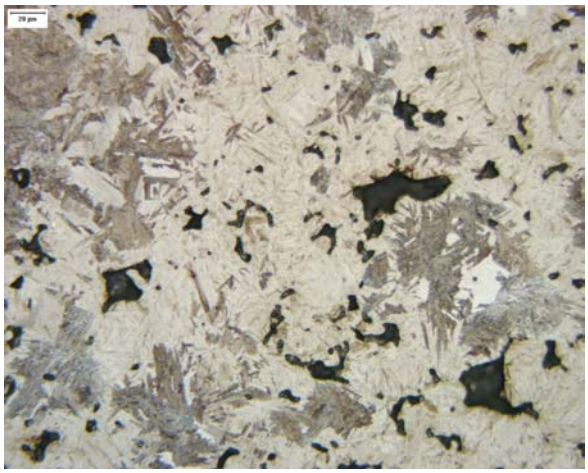


Figure 7c: Astaloy Mo + 2% Cu + 0.75% C
T=1120 °C dT/dt=2-3 °C/s

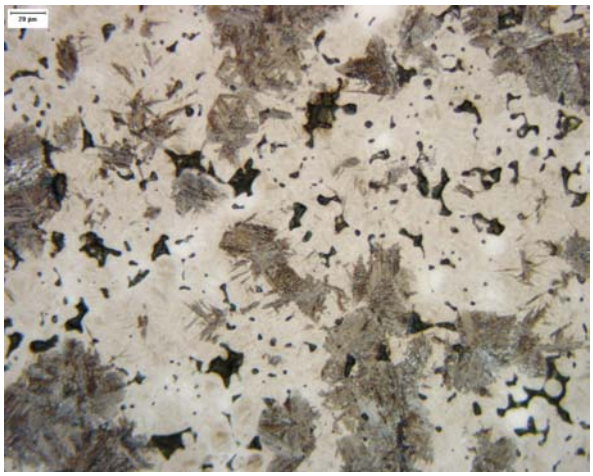


Figure 7d: Astaloy Mo +2% Ni + 0.7% C
T=1120 °C dT/dt=2-3 °C/s

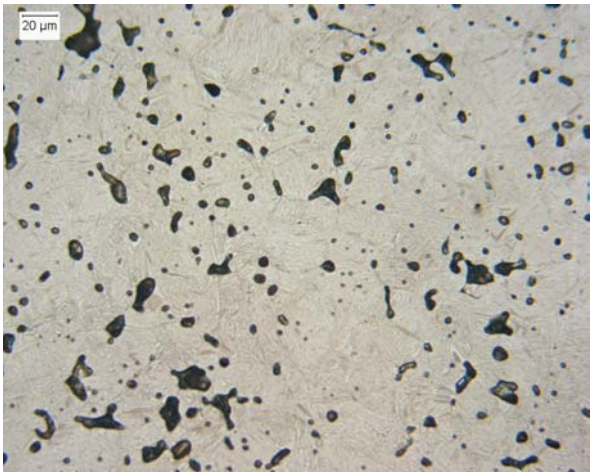


Figure 7e: Astaloy CrM + 0.45% C
T=1250 °C dT/dt=2-3 °C/s

The increase in impact energy with raised cooling rate at 1250 °C for the Astaloy A, Astaloy CrM and Astaloy Mo material with copper additions is unexpected In fact the quantity of martensite in the microstructure increases. The fracture surfaces (impact energy sample) of the Astaloy A and Astaloy CrM materials sintered at 1250 °C after slow and fast cooling were studied in a scanning electron microscope. See Figures from 8a to 8d, showing portions of fracture surfaces. The Astaloy A material, slow and fast cooled showed overall a ductile fracture with dimples. However, in the slow cooled samples areas with cleavage features, indicating a brittle behaviour of the material, were observed (see Figure 8a). In the fast cooled sample isolated areas showing inter-granular features were found, indicating a less brittle behaviour, if compared to the slow cooled samples. Similar behaviour could be expected for the Astaloy Mo material with copper additions.

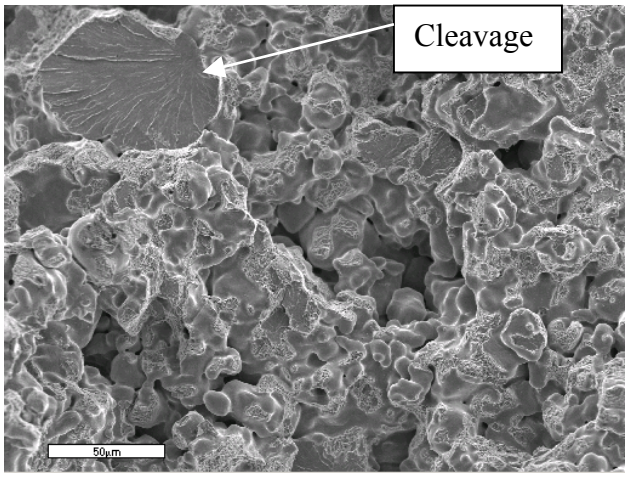


Figure 8a: Astaloy A+2%Cu+0.70%C
T=1250 °C dT/dt= 0.25-0.8 °C/s

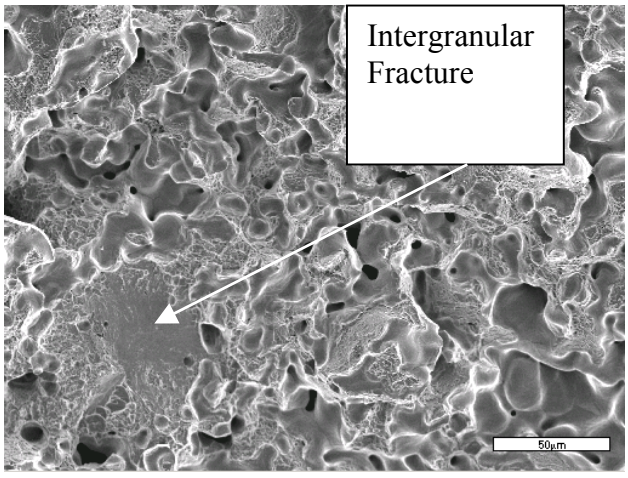


Figure 8b: Astaloy A+2%Cu+0.70%C
T=1250 °C dT/dt=2-3°C/s

The fracture surface of the slow cooled Astaloy CrM material shows both dimples, and brittle fracture features: cleavage and especially inter-granular fracture areas. After rapid cooling the fracture surface is overall ductile with few localised areas where the crack propagation gives rise to brittle cracking feature on the threshold of inter-granular fracture.

SEM observation confirms then the more ductile behaviour of the rapidly cooled materials as a larger amount of dimples is observed if compared to the slow cooled materials. SEM investigation also shows that the higher impact energy observed for the Astaloy CrM material, if compared to Astaloy A,

after slow cooling is due to a larger amount of cleavage features in the Astaloy A material; after rapid cooling inter-granular fracture features are present in larger amount in the Astaloy A material.

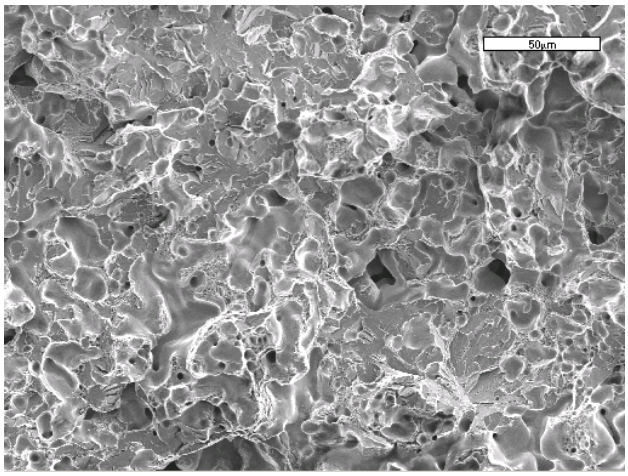


Figure 8c: Astaloy CrM+0.45%C
T=1250 °C, dT/dt=0.25-0.8 °C/s

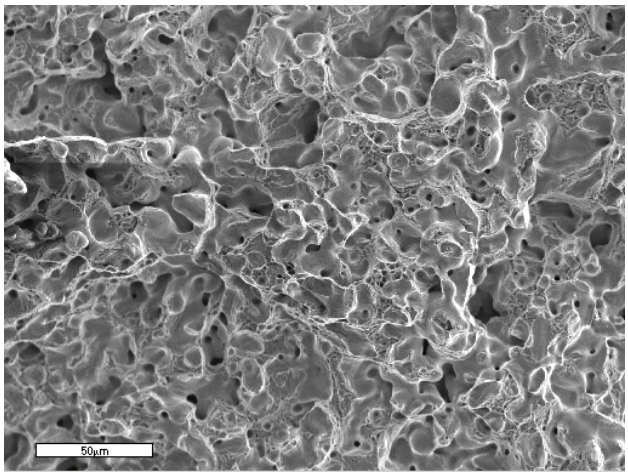


Figure 8d: Astaloy CrM+0.45%C
T=1250 °C, dT/dt=2-3 °C/s

The higher the sintering temperature, the larger the shrinkage. Normally the greater the shrinkage the more difficult it is to keep tight dimensional tolerances. Astaloy CrM is dimensionally more stable if compared to Astaloy A with copper additions both when sintering at 1120 °C and at 1250 °C. The difference in scatter is larger at the sintering temperature of 1250 °C. The scatter in base tangent length, which is an important parameter for the function of a gear, is more than double for the Astaloy A materials with copper, if compared to Astaloy CrM.

CONCLUSIONS

- When increasing the cooling rate from 0.25-0.8 °C/s to 2-3 °C/s at 1120 °C:
  - tensile strength is increased by 10-35%
  - yield strength is increased by 15-50%

- When increasing the cooling rate from 0.25-0.8 °C/s to 2-3 °C/s at 1250 °C:
  - tensile strength is increased by 25-70%
  - yield strength is increased by 35-70%

- When increasing the sintering temperature from 1120 °C to 1250 °C at the cooling rate of 2-3 °C/s
  - tensile strength is increased by 15-40%
  - yield strength is increased by 10-30%

- Astaloy CrM achieves highest strength combined with highest elongation when sintering at 1250 °C both at slow and fast cooling rate. A tensile strength of 1420 MPa combined with an elongation of 1% is obtained.

- Astaloy CrM is dimensionally more stable if compared to Astaloy A, especially when sintering at 1250 °C.

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