

EVALUATION OF SINTER HARDENING OF DIFFERENT PM MATERIALS

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ABSTRACT

The development of new materials and cost effective processes are two main factors that have contributed to the growth of PM parts during the last decade. 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. 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. Alloying elements such as molybdenum, chromium, nickel and copper all promote hardenability. By increasing the hardenability of the material still large amounts of martensite can be obtained also at slower cooling rates.

In this paper a number of different PM materials are evaluated after sinter-hardening. The influence of alloying system and cooling rate on both microstructure and mechanical properties will be discussed.

INTRODUCTION

Sinter-hardening is a one step process that combines good manufacturing economy with the ability to achieve a unique combination of mechanical properties (1,2). 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. A material with high hardenability is one in which austenite is able to transform to martensite without forming pearlite, even when the rate of cooling is rather slow. By alloying the materials, the hardenability increases and more martensite can be produced at similar cooling rates and thereby increase the mechanical strength of the parts. Alloying elements such as molybdenum, copper, nickel and chromium all promote hardenability and are all utilised in the materials described in this paper.

It is important to remember that in addition to composition and microstructure, density plays an important role in the determination of properties. It is a well known fact that increases in density significantly improve the material properties. As density levels are increased, not only do hardness and strength values increase, but ductility values such as tensile elongation and impact properties are increased dramatically. Therefore the different materials described in this paper were evaluated at two density levels, 7.0-7,1 g/cm³ and 7.2-7,3 g/cm³, to compare the properties obtained after sinter hardening.

EXPERIMENTAL PROCEDURE

Materials

In order to evaluate the effect of cooling rate on the performance of several materials composition and, eight different powder mixes were made. The base powders used for the mixes were two diffusion alloyed powders, D.DC-1 and D.DH-1 and two pre-alloyed powders Astaloy A and Astaloy CrM. The D.DC-1 powder is based on a fully pre-alloyed powder with 1,5% Mo to which 2% Ni has been diffusion alloyed. D.DH-1 is based on the same prealloyed powder but is diffusion alloyed with 2% Cu. Astaloy A is a fully pre-alloyed powders with 1,9% Ni and 0,5% Mo whereas Astaloy CrM is a fully pre-alloyed powder containing 3% Cr and 0,5% Mo

The compositions of the mixes prepared are shown in Table 1. In the mixes used for cold compaction 0.60 % Kenolube was added as lubricant. For warm compaction four different Densmix powders containing 0,6 % lubricant were prepared The copper admixed to Astaloy A was -325 mesh electrolytic copper powder, and the graphite used in all cases was UF-4 from Kropfmuhl.

Table 1. Compositions of the powder mixes used.

Powder	Ni %	Cu %	Mo %	Cr %	Gr. %	Lub. % Cold	Lub. % Warm
D. DC-1	2,0		1,5		0,7	0,6	0,6
D. DH-1		2,0	1,5		0,7	0,6	0,6
Astaloy A	1,90	2,0	0,5		0,7	0,6	0,6
Astaloy CrM			0,5	3,0	0,4	0,6	0,6

Processing conditions

The processing conditions used to produce the test specimens are shown in Table 2 below. The specimens, tensile test bars and impact energy bars according to ISO standards were compacted in a Tonitechnik 100 ton, semi-automatic laboratory press, to two different density levels, 7.10 g/cm³ by conventional compaction and 7.30 g/cm³ by using warm 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 Abbott equipped with VARICOOL 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 °C (2050 °F). Sintering time was 30 min at temperature and the atmosphere used was 90/10 mix of nitrogen and hydrogen. Two different cooling rates settings were used, 10 Hz and 60 Hz respectively. The 60 Hz setting represents the maximum cooling capability of the VARICOOL system.

After sintering tempering was carried out at 200 C (390 F) for 60 minutes in air.

Table 2. Processing conditions used to produce test specimens.

Powder	D. DC-1	D. DH-1	Astaloy A	Astaloy CrM
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Compaction Pressure, MPa / tsi Cold (GD 7,00) Warm (GD 7,30)	600 / 45 725 / 52	600 / 45 725 / 52	725 / 52 900 / 64	725 / 52 900 / 64
Sintering Temperature, °C / °F Time, min Atmosphere	1120 / 2050 30 90N ₂ /10 H ₂	1120 / 2050 30 90N ₂ /10 H ₂	1120 / 2050 30 90N ₂ /10 H ₂	1120 / 2050 30 90N ₂ /10 H ₂
Cooling rate, Hz	10 60	10 60	10 60	10 60
Tempering Temperature, °C / °F Time, min Atmosphere	200 / 390 60 Air	200 / 390 60 Air	200 / 390 60 Air	200 / 390 60 Air

Testing

After the final tempering operation, apparent hardness measurements were performed on the surface of the specimens using a Rockwell hardness tester. All of the testing was performed on the Rockwell C scale for comparison purposes. Tensile testing was performed in a MTS Sintech 20D tensile testing machine. The gauge length was 25 mm (1 inch) and the specimens were pulled at 1mm/min. Impact energy tests were carried out in a Charpy tester

Metallography

The tensile bars were sectioned and prepared for metallographic analysis. Photomicrographs were taken of the structures after etching in Pikral 4% for the D.DC-1 and D.DH-1 and etchant 3.3 for the other materials. The martensite and bainite content was determined utilizing point count analysis. This analysis technique included the porosity as a portion of the total microstructure. The reported percentages were corrected for the porosity present in the materials.

RESULTS AND DISCUSSION

Green and sintered density

The green and sintered densities obtained for the four materials after conventional cold compaction and sintering are shown in Table 3. As can be seen the density obtained after compaction is 7,00 g/cm³ for all powders. However after sintering the materials show two groups regarding the density. One for D.DC-1 and Astaloy CrM which both achieve a density in a range of 7.06-7.10 g/cm³ while the other group consisting of D.DH-1 and Astaloy A/ 2Cu obtain about 0.10 g/cm³ lower density, 6,96-6,97 g/cm³. The different behaviour of the materials during sintering will be discussed in more detail in the dimensional change part later in this paper.

Table 3. Green and sintered densities obtained after cold compaction

Powder	D. DC-1	D. DH-1	Astaloy A	Astaloy CrM
Green density, g/cm ³	7,00	7,00	7,00	7,00
Sintered density, g/cm ³				
10 Hz	7,10	6,96	6,97	7,06
60 Hz	7,09	6,96	6,97	7,06

The green and sintered densities obtained after warm compaction and sintering are shown in Table 4 below. It can be seen that the density obtained after warm compaction is 7,30 g/cm³ for all powders. Also in this case two groups regarding densities are formed after sintering. D.DC-1 and Astaloy

CrM both achieved a density of 7,30 g/cm³ while D.DH-1 and Astaloy A/ 2Cu obtained about 0.10 g/cm³ lower density, 7,19-7,20 g/cm³.

From the results it is also clear that the difference in cooling rate has no influence on the density for any of the materials.

Table 4. Green and sintered densities obtained after warm compaction

Powder	D. DC-1	D. DH-1	Astaloy A	Astaloy CrM
Green density, g/cm ³	7,30	7,30	7,30	7,30
Sintered density, g/cm ³				
10 Hz	7,31	7,20	7,20	7,30
60 Hz	7,30	7,21	7,19	7,30

Dimensional change

The dimensional change obtained for the four materials during sintering is shown in Table 5. As can be seen the materials based on D.DH-1 and Astaloy A /2Cu show a swelling of about 0,2-0,3 % depending on the processing conditions. This is due to alloying with copper Cu which promotes growth during sintering. Regarding D.DC-1 and Astaloy CrM they both show a slight shrinkage during sintering. The shrinkage is also more insensitive to the processing conditions compared to the two materials containing copper.

Table 5. Effect of processing conditions on dimensional change

	Processing conditions		Material			
	Compaction mode	Cooling rate	D. DC-1	D. DH-1	Astaloy A	Astaloy CrM
Dimensional change, %	Cold	10 Hz	-0,06	0,16	0,28	-0,10
		60 Hz	-0,05	0,20	0,30	-0,08
Dimensional change, %	Warm	10 Hz	-0,14	0,31	0,33	-0,08
		60 Hz	-0,07	0,35	0,36	-0,05

Hardness

The apparent hardness obtained with different cooling rates for the conventional cold compacted materials are shown in Table 6. The two copper containing materials have achieved a higher hardness compared to the D.DC-1 and Astaloy CrM based materials at the lower cooling rate settings of 10Hz. The difference in hardness levels can be explained by the microstructures obtained and will be described later in this paper. At the higher cooling rate 60 Hz all materials obtained a significantly higher hardness level which is also similar for the four different materials. The increase in hardness level obtained by the increased cooling rate is due to the high martensite content formed at this cooling condition. The slightly lower hardness levels obtained with the Astaloy CrM material is due to the lower carbon content.

Table 6. Hardness of cold compacted samples after sintering and tempering

	Cooling rate	Material			
		D. DC-1	D. DH-1	Astaloy A	Astaloy CrM
Hardness, HRC	10 Hz	25	30	34	24
Hardness, HRC	60 Hz	40	37	37	35

The hardness obtained with different cooling rates for the warm compacted materials are shown in Table 7. Also in this case the two copper containing materials achieved a higher hardness level at the

lower cooling rate setting compared to the copper free materials. At the higher cooling rate all materials obtained a significantly higher hardness level. The highest hardness levels were obtained for the two diffusion alloyed materials. The Astaloy A based material showed the smallest increase but had on the other hand a higher hardness than the other materials already at the lower cooling rate setting. The hardness levels obtained for Astaloy CrM is about the same as for the Astaloy A based material but slightly lower than the hardness of the two diffusion alloyed materials. This is mainly due to the low carbon content of the material. The influence of carbon content on the properties of Astaloy CrM will be discussed below.

Table 7. Hardness of warm compacted samples after sintering and tempering

	Cooling rate	Material			
		D. DC-1	D. DH-1	Astaloy A	Astaloy CrM
Hardness, HRC	10 Hz	30	36	36	29
Hardness, HRC	60 Hz	45	44	39	40

A comparison of the hardness levels obtained at the two different density levels is shown in Figure 1 for the lower cooling rate setting, 10 Hz, and in Figure 2 for the higher one at 60 Hz. As can be seen the hardness has increased for all materials at both cooling conditions when the density is increased which is to be expected.

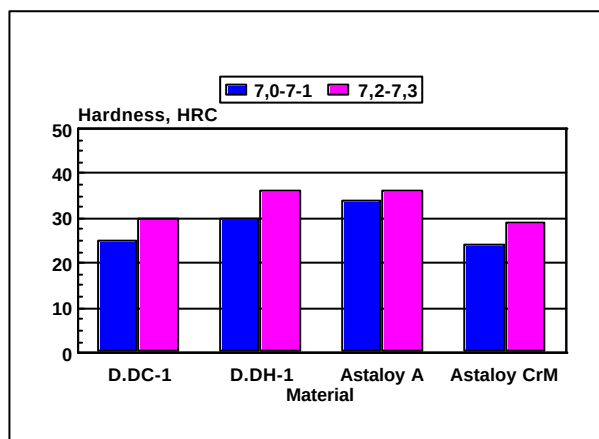


Figure 1. Hardness at different density levels low cooling rate setting of 10 Hz

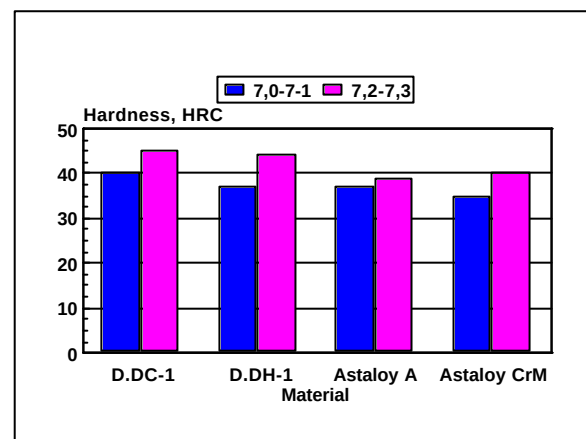


Figure 2. Hardness at different density levels after high cooling rate setting of 60 Hz

Effect of carbon content in Astaloy CrM

The influence of carbon content on the properties of Astaloy CrM is showed in Figure 3. The hardness values are obtained for the lower density level of $7,1 \text{ g/cm}^3$ and the lower cooling rate setting. As can be seen the hardness increased from about 24 HRC at 0,35%C to 45 HRC at a carbon content of 0,55 %.

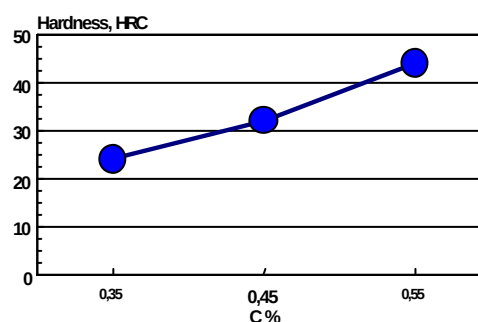


Figure 3. Effect of carbon content on hardness of Astaloy CrM

Mechanical properties

The mechanical properties obtained after conventionally cold compacted powders. It can be seen that both the ultimate tensile strength and the

Table 8 for the

0.2% offset yield strength values for all materials showed increased levels with increasing cooling rate. The tensile strength increased about 20% from 752 to 897 MPa (107,000 to 128,000 psi) for D.DC-1 and more than 30% from 817 to 1078 MPa (117,000 to 154,000 psi) for the Astaloy CrM material which reached a very high tensile strength level at the high cooling rate setting. For the D.DH-1 and Astaloy A based materials the increase in tensile strength were much smaller, 5 and 2 % respectively. On the other hand the tensile strength levels for these two materials, especially Astaloy A, were higher at the lower cooling rate setting compared to D.DC-1 and Astaloy CrM.

The increase in cooling rate resulted in improvements in yield strength from 597 to 840 MPa (85,000 to 120,000 psi) or 24% for the D.DC-1 based material and more than 40 % for the Astaloy CrM material, from 638 to 898 MPa (91,000 to 128,000 psi). The increase in yield strength was smaller for the D.DH-1 and Astaloy A based materials, 19 and 10% respectively.

All four materials show similar yield strength levels, about 840 –900 MPa (120,000 to 128,000 psi) when cooled at the higher cooling rate setting. Similar to the tensile strength results the Astaloy A based material showed the highest yield strength at the lower cooling condition.

Regarding elongation Astaloy CrM showed the highest value of all materials at the lower cooling rate, 1%. D.DC-1 obtained 0,8% and the other two materials about 0,5%. At the higher cooling rate setting of 60 Hz the elongation dropped for all materials. Still the Astaloy CrM material showed the highest value, 0,6%.

By comparing the impact energies obtained for the four materials it can be seen that the D.DC-1, D.DH-1 and Astaloy A based materials achieved about the same level, 14-16 J (8,8-9,3 ft/lbf) at the two different cooling conditions while Astaloy CrM obtained the highest values. The impact energy at the lower cooling rate was 18 J (11,0 ft/lbf) and decreased to 16,8 J (10,1 ft/lbf) at the higher cooling condition.

Table 8. Mechanical properties of cold compacted samples after sintering and tempering

Material	D. DC-1	D. DH-1	Astaloy A	Astaloy CrM
Cooling rate 10 Hz				
Sintered density, g/cm ³	7,10	6,96	6,97	7,06
Dimensional change, %	-0,08	0,15	0,29	-0,10
Tensile strength, MPa / ksi	752 / 107	866 / 124	930 / 133	817 / 117
Yield strength, MPa / ksi	597 / 85	746 / 106	797 / 114	638 / 91
Elongation, %	0,8	0,5	0,4	1,0
Impact energy, J / ft/lbf	14,6 / 8,8	15,0 / 9,0	14,5 / 8,7	18,2 / 11,0
Cooling rate 60 Hz				
Sintered density, g/cm ³	7,09	6,96	6,98	7,06
Dimensional change, %	-0,05	0,20	0,30	-0,08
Tensile strength, MPa / ksi	897 / 128	911 / 130	947 / 135	1078 / 154
Yield strength, MPa / ksi	840 / 120	885 / 126	879 / 126	898 / 128
Elongation, %	0,3	0,3	0,3	0,6
Impact energy, J / ft/lbf	14,9 / 9,0	14,6 / 8,8	15,5 / 9,3	16,8 / 10,1

In Table 9 the mechanical properties for the warm compacted powders after sintering and different cooling conditions are shown. As can be seen the trends are similar to the ones described for the cold compacted materials. However the tensile and yield strength levels are considerably higher for all materials in this case. This is due to the higher densities obtained with warm compaction.

Table 9. Mechanical properties of warm compacted samples after sintering and tempering

Material	D. DC-1	D. DH-1	Astaloy A	Astaloy CrM
Cooling rate 10 Hz				
Sintered density, g/cm ³	7,30	7,20	7,20	7,30
Dimensional change, %	-0,14	0,31	0,33	-0,08
Tensile strength, MPa / ksi	967 / 138	1102 / 157	1001 / 143	969 / 138
Yield strength, MPa / ksi	700 / 100	836 / 119	865 / 124	729 / 104
Elongation, %	1,5	0,9	0,5	1,3
Impact energy, J / ft/lbf	23,2 / 14,0	21,1 / 12,7	19,5 / 11,7	15,0 / 9,0
Cooling rate 60 Hz				
Sintered density, g/cm ³	7,30	7,21	7,19	7,30
Dimensional change, %	-0,07	0,36	0,36	-0,05
Tensile strength, MPa / ksi	1234 / 176	1214 / 173	1163 / 166	1264 / 181
Yield strength, MPa / ksi	1075 / 154	1093 / 156	1053 / 150	1046 / 149
Elongation, %	0,5	0,4	0,4	0,7
Impact energy, J / ft/lbf	22,0 / 13,3	17,5 / 10,5	18,0 / 10,8	14,1 / 8,5

The tensile strength increased about 25% from 967 to 1234 MPa (138,000 to 176,000 psi) for D.DC-1 and more than 30% for the Astaloy CrM material from 969 to 1264 MPa (138,000 to 181,000 psi) when the cooling rate was increased. The D.Dh-1 based material achieved a tensile strength of about 1100 MPa (157,000 psi) already at the lower cooling rate setting of 10 Hz and increase with about 100 MPa to 1214 MPa (173,000 psi) when the cooling rate was increased. The tensile strength of the Astaloy A based material increased about 15 % from 1000 MPa (143,000 psi) to 1163 MPa (166,000 psi).

By increasing the cooling rate yield strength was increased for all four materials to about the same high levels of 1050-1100 MPa (150,000 to 156,000 psi). The increase was largest for the D.DC-1 and Astaloy CrM based materials, 53 and 43% respectively. At the lower cooling rate setting Astaloy A and D.DH-1 obtained the highest yield strength levels.

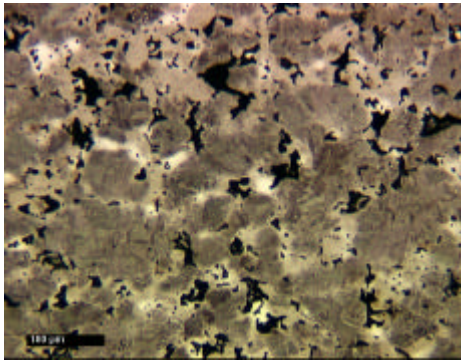
Regarding elongation D.DC-1 and Astaloy CrM showed the highest values, 1,5% and 1,3% respectively, compared to 0,9 and 0,5 % for the D.DH-1 and Astaloy A based materials at the lower cooling rate. At the higher cooling rate setting the elongation dropped for all materials to a level of about 0,5%.

By comparing the impact energies obtained for the four materials it can be seen that the D.DC-1, D.DH-1 based materials achieved the highest levels, 23,2 and 21,1 J (14,0 and 12,7 ft/lbf) respectively at the lower cooling condition. These high levels of impact energy is due to the density and to the microstructure obtained after sintering. The Astaloy A based material showed 19,5 J (11,7 ft/lbf) while Astaloy CrM obtained the lowest value, 15,0 J (9,0 ft/lbf).

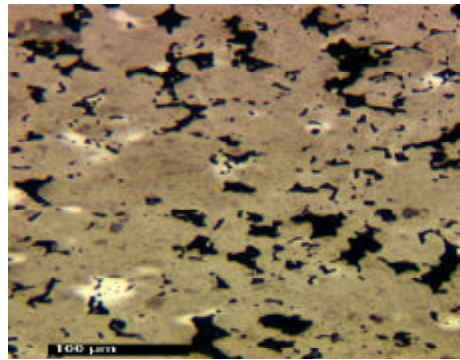
At the higher cooling rate setting all materials show a drop in impact energy. However the D.DC-1 based material still show a very high level 22 J (13,3 ft/lbf). D.DH-1 and Astaloy A show a decrease to 17,5 and 18 J (10,5 and 10,8 ft/lbf) respectively while Astaloy CrM decreased to 14,1 J (8,5 ft/lbf). The high level obtained for D.DC-1 is due to both density and microstructure which will be discussed in the next part.

MICROSTRUCTURES

Photomicrographs of the microstructures obtained for the four materials are shown in Figures 3-6. All photomicrographs show the materials at the lower density level 7,0-7,1 g/cm³ at the two different cooling rate settings 10 and 60 Hz. By comparing the microstructures achieved with the two different cooling rates for each material it is clear that the amount of martensite present has increased significantly with the increase in cooling rate. The effect of the increased martensite content in the microstructure is apparent in the hardness values obtained for each of the materials as already described above. The higher levels of martensite present in the microstructure also explain the increase in tensile and yield strength as well as the decrease in elongation and impact energy.

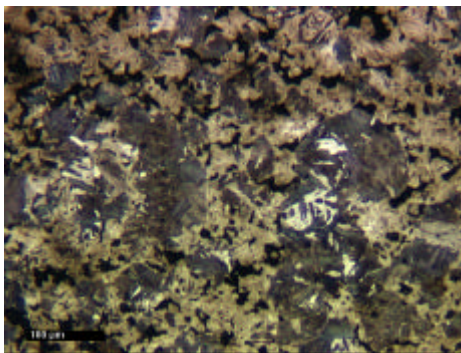


D. DC-1 7,10 g/cm³, 10 Hz

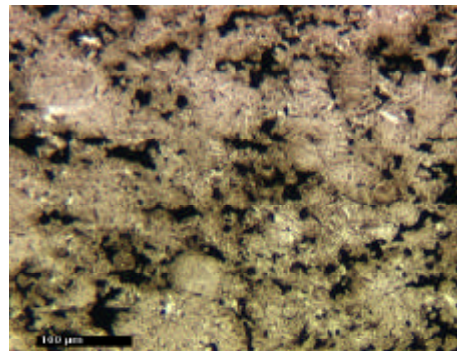


D. DC-1 7,10 g/cm³, 60 Hz

Figure 3. Microstructures of D.DC-1 at different cooling rates

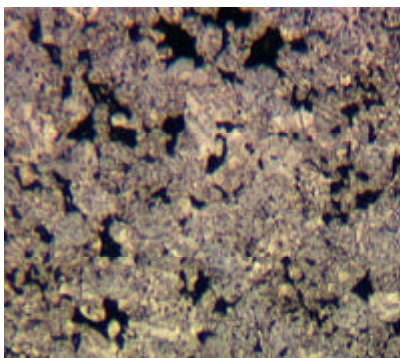


D. DH-1 7,10 g/cm³, 10 Hz

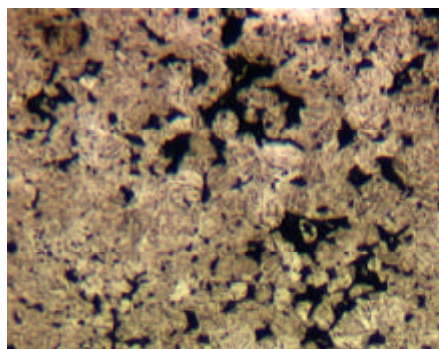


D. DH-1 7,10 g/cm³, 60 Hz

Figure 4. Microstructures of D DH-1 at different cooling rates



Astaloy CrM 7,10 g/cm³, 10 Hz



Astaloy CrM 7,10 g/cm³, 60 Hz

Figure 5. Microstructures of Astaloy A/ 2Cu at different cooling rates

Figure 6. Microstructures of Astaloy CrM at different cooling rates

The amount of the different phases present in each material have also been determined and the result is presented in Table 10. By comparing the results at the lower density level 7,0-7,10 g/cm³ and the lower cooling rate setting (10 Hz) first it can be seen that the four different materials show big differences regarding the amount of bainite and martensite present in the microstructure. The D.DC-1 material contained ~75% bainite and ~25 % martensite and about 1-2 % of retained austenite due to remaining areas with high nickel content. This is a result of the diffusion alloying of Ni and the too short sintering time to create a homogeneous distribution of Ni in the material. The D.DH-1 based material show a higher amount of martensite, ~60 %, and ~40% bainite and consequently the hardness values are higher than for D.DC-1. The Astaloy A based material show the highest amount of martensite, ~85 %, of all materials at this cooling condition and ~15 % of bainite. This explains why the hardness level of this material achieved the highest values at this cooling rate setting. Astaloy CrM showed the lowest amount of martensite, ~15%, at the low cooling condition and about 90 % of bainite. This explains the low hardness values obtained and is due to the low carbon content as already discussed above.

Table 10. Effect of cooling rate on amount of martensite and bainite

Density, g/cm ³	Cooling rate	Microstructure	Material			
			D. DC-1	D. DH-1	Astaloy A	Astaloy CrM
7,0-7,1	10 Hz	Bainite,%	75	40	15	90
		Martensite, %	25	60	85	10
	60 Hz	Bainite,%	1	0	2	0
		Martensite, %	99	100	98	100
7,2-7,3	10 Hz	Bainite,%	75	35	15	90
		Martensite, %	25	65	85	10
	60 Hz	Bainite,%	1	0	1	0
		Martensite, %	99	100	99	100

Regarding the microstructures obtained for the four materials at the higher cooling rate settings at 60 Hz it can be seen that the amount of martensite present has increased significantly in each material with the increase in cooling rate. For the D.DH-1 and Astaloy CrM based materials the microstructure is completely martensitic and for the D.DC-1 and Astaloy A based material there is 1-2 % of bainite remaining. The D.DC-1 material also contains some nickel rich areas which remains as white spots in the microstructure and consists of retained austenite. The formation of a more or less martensitic structure is apparent in the hardness values obtained for each of the materials as already described. The higher levels of martensite present in the microstructure also explain the increase in tensile and yield strength for all materials as described earlier as well as the decrease in elongation and impact energy.

Table 10 also shows the result of the phase analysis carried out for the specimens at the higher density level. As can be seen the amount of the different phases are almost the same as the amounts obtained at the lower density level for all materials. Therefore it can be concluded that the density does not have any significant influence on the microstructure at the density levels studied.

Phase amount versus cooling rate for D.DH-1

An interesting question is what the cooling rate settings 10 and 60 Hz of the VAARICOOOL system correspond to in °C / sec. This question can be answered by comparing the results from the actual phase amount analysis described previously with available phase amounts diagram derived from

CCT diagrams and analysis of samples cooled at different rates using a dilatometer. In Figure 7 below such a phase amount diagram for D.DH-1 is shown (3). As already described the lower setting at 10 Hz resulted in a microstructure containing ~60% martensite and 40 % bainite. By comparing these values with the lines derived for the amounts of martensite and bainite respectively in the diagram it can be concluded that the 10 Hz setting corresponds to a cooling rate of $\sim 2^{\circ}\text{C} / \text{second}$ ($\sim 4^{\circ}\text{F}/\text{sec}$). Doing the same with the result of the phase analysis from the 60 Hz setting show that this corresponds to a cooling rate of $5\text{-}6^{\circ}\text{C}/\text{sec}$ ($10\text{-}12^{\circ}\text{F} / \text{sec}$).

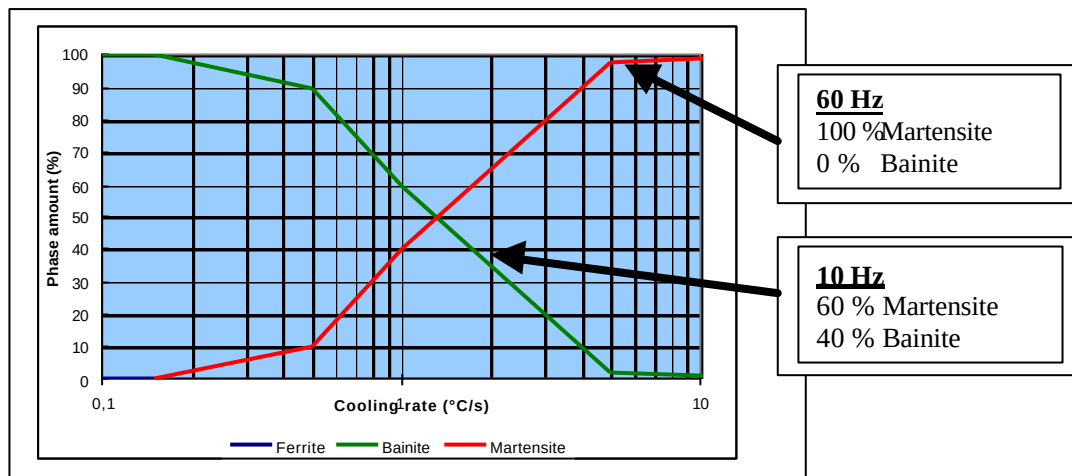


Fig.7 Effect of cooling rate on microstructure of D.DH-1

CONCLUSIONS

The effect of post sintering cooling rate on microstructure and the resulting mechanical properties of the two diffusion alloyed materials D.DC-1 and D.DH-1 and two fully pre-alloyed materials Astaloy A with 2% Cu addition and Astaloy CrM can be summarised as follows:

All four materials are suitable for sinter hardening especially at higher cooling rate settings corresponding to cooling rates higher than $3\text{-}4^{\circ}\text{C} / \text{sec}$ ($5\text{-}7^{\circ}\text{F} / \text{sec}$).

At lower cooling rates $1\text{-}2^{\circ}\text{C} / \text{sec}$ ($2\text{-}4^{\circ}\text{F} / \text{sec}$) the Astaloy A / 2%Cu material show the highest values regarding hardness and strength at both density levels studied which is due to the high martensite content achieved in the microstructure.

As the cooling rate was increased the apparent hardness increased for all materials. This was associated with higher martensite contents in the faster cooled materials. Martensite contents of 100% were found in Astaloy CrM and D.DH-1 and about 98 % in the D.DC-1 and Astaloy A based materials when maximum cooling rate was utilized.

Accelerated cooling resulted in increased tensile and yield strength values. At the high cooling rate setting, 60 Hz, tensile strength levels exceeding 1200 MPa were obtained for the diffusion alloyed materials and for Astaloy CrM. At this cooling rate yield strength between 1000 and 1100 MPa were obtained for all materials.

To fully utilise the beneficial effect of chromium as an alloying element in sinter hardening it is recommended to use a carbon content of 0,4-0,6%. At the higher carbon level the cooling rate does not have to be more than $0,5\text{-}1,0^{\circ}\text{C}/\text{sec}$ ($1\text{-}2^{\circ}\text{F}/\text{sec}$) to reach hardness levels exceeding 35 HRC

The D.DC-1 based material shows a very good combination of hardness, tensile and yield strength with high impact energy at the higher density level of $7,30 \text{ g}/\text{cm}^3$.

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