Influence of sintering temperature on properties of low alloyed high strength PM materials

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ABSTRACT

New applications for PM steels are continuously introduced on the market. This is primarily due to development taking place within the PM industry but also a result of new designs of engines etc. Many of these new applications utilise the unique possibilities of PM to achieve high strength in combination with close dimensional tolerances with a minimum of manufacturing operations

The diffusion alloyed materials D.AE and D.HP-1 and the completely prealloyed material Astaloy CrM are all aimed for applications combining high strength with close dimensional tolerances. These materials reach tensile strength levels in the range of 850 MPa to 1000 MPa after conventional compaction at room temperature and sintering in belt furnaces at1120°C/ 2048°F. By applying high temperature sintering i.e sintering at temperatures >1200°C/ 2200°F, these strength levels can be increased. By combining high temperature sintering with warm compaction PM materials with even higher strength levels can be obtained.

In this paper the influence of sintering temperature on static properties for both conventionally and warm compacted D.AE, D.HP-1 and Astaloy CrM is described. The effect of using higher sintering temperatures than 1120°C/2048°F on the dimensional change for these materials is also presented.

INTRODUCTION

The development of new steel powders and processes during the last decades has led to a considerably expansion of the applications for PM. In order to further extend the applications for PM there is a demand for alloy systems as well as processes which result in improved mechanical properties with maintained precision of tolerance control at reduced costs.

In this paper the influence of sintering temperature on static properties for both conventionally and warm compacted D.AE, D.HP-1 and Astaloy CrM is described. The effect of using higher sintering temperatures than 1120°C in combination with increased cooling rate for these materials is also presented.

POWDERS AND PROCESSING CONDITIONS

The powders and processing conditions used are showed in fig 1 below. Green and sintered properties were analysed according to standardised test methods.

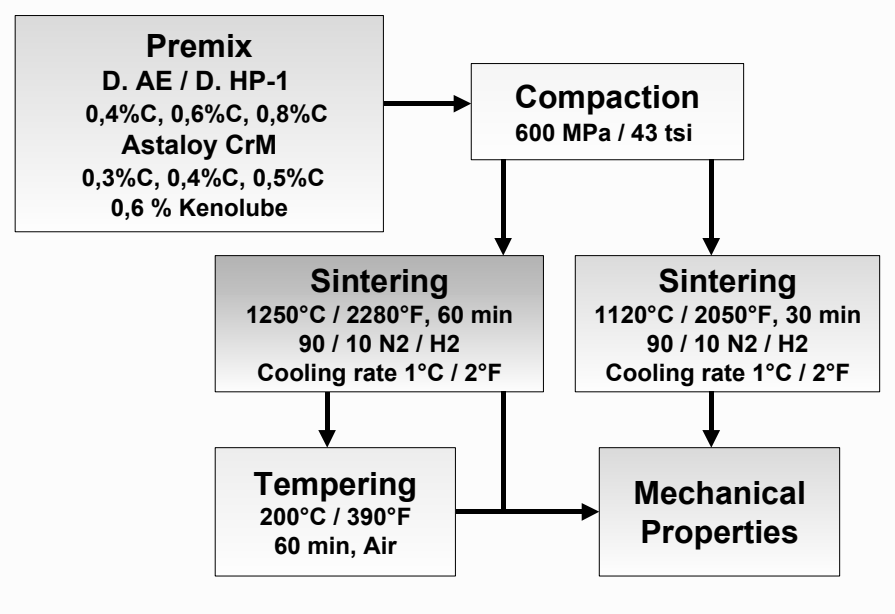


Fig 1. Powders and processing conditions used.

D. AE is a diffusion alloyed powder containing 4% Ni, 1,5 % Cu and 0,5% Mo based on the high compressibility iron powder ASC 100.29. D. HP-1 is based on a 1,5% Mo pre-alloyed powder (Astaloy Mo) and diffusion bonded with 4% Ni, 2 % Cu. Astaloy CrM is a fully pre-alloyed powder containing 3% Cr and 0,5% Mo.

SINTERED DENSITY AND DIMENSIONAL CHANGE

In table 2 below a comparison of the sintered densities obtained for the three materials at the low carbon level i.e. 0,4% for D. AE and D. HP-1 and 0,3% for Astaloy CrM are shown after compaction at 600 MPa and sintering at 1120°C / 2050°F and 1250°C / 2280°F respectively.

Table 2. Typical sintered density levels of different powders after compaction at 600 MPa and sintering at 1120°C / 2050°F and 1250°C / 2280°F respectively.

Sintering temperature	Powder	D. AE	D. HP-1	Astaloy CrM
1120°C / 2050°F	Sintered density, g/cm^3	7,08	7,01	9,94
1250°C / 2280°F	Sintered density, g/cm^3	7,16	7,10	7,01

The highest densities are obtained with the D. AE powder which is due to the high compressibility of the base iron powder, ASC 100.29, used for this grade. The green density obtained with the D. HP-1 based mixes is slightly lower than the D.AE based mixes after compaction with the same pressures which is related to the somewhat lower compressibility of Astaloy Mo which is the base for D. HP-1. The Astaloy CrM based mixes achieved about 0,10 g/cm^3 lower density than for D. HP-1. This is due to the somewhat lower compressibility of the Astaloy CrM base powder due to its higher pre-alloying content.

Dimensional change

The dimensional change obtained for the three materials discussed above during sintering at the two different temperatures used are shown in fig 2 below. The dimensional change achieved when sintering at 1120°C / 2050°F showed a shrinkage of about 0,10 % for the two diffusion alloyed materials whereas the Astaloy CrM based material shrank slightly more 0,20%. When the sintering temperature was increased to 1250°C / 2280°F the shrinkage increased for all three materials. Still the Astaloy CrM showed the largest shrinkage, -0,60%, compared to 0,40% for the two diffusion alloyed materials. This increased shrinkage explains the increased densities observed above for the materials sintered at higher temperature.

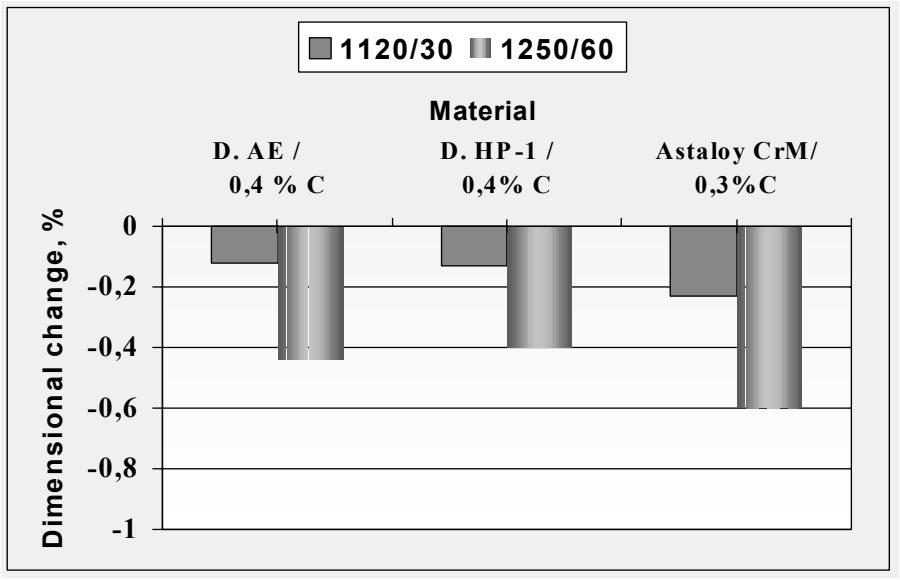


Fig. 2 Dimensional change obtained during sintering at the different sintering temperatures used for the different powders.

MECHANICAL PROPERTIES

Tensile strength

The tensile strength obtained for the three materials at the different carbon contents are shown in fig 3 below. It can be seen that in general the tensile strength increased for all materials sintered at the higher temperature of 1250°C / 2280°F compared to the materials sintered at 1120°C / 2050°F except for D. HP-1 containing 0,8% carbon.

At the lower sintering temperature of 1120°C/2050°F the highest tensile strength was achieved with D. HP-1 at the two lower carbon levels, 890 MPa/ 127 ksi at 0,4%C and 940 MPa/ 134 ksi at 0,6%C. However at 0,8% C the tensile strength dropped about 15 %.

At the higher sintering temperature a considerably higher tensile strength of 1144 MPa/163 ksi was obtained for the D.HP-1 material with 0,4%C.. At the two higher carbon levels the strength dropped especially for the material containing 0,8%. This is due to the microstructure transforming into a martensite with high carbon. Optimum carbon content for this material is 0,5%C.

The tensile strength of the D. AE and Astaloy CrM based material are about the same when sintered at 1120°C/2050°F for all three carbon levels. However the tensile strength of the D. AE based material sintered at this temperature decreased with increasing carbon content wheras the Astaloy CrM based materials all increased.

At the higher temperature the tensile strength lincreased with the Astaloy CrM material for all carbon levels. The increase was largest at 0,4 and 0,5%. At these carbon contents tensile strength levels close to 1000 MPa / 143 ksi were reached. Regarding the D. AE the tensile strength increased for the two lower carbon contents.

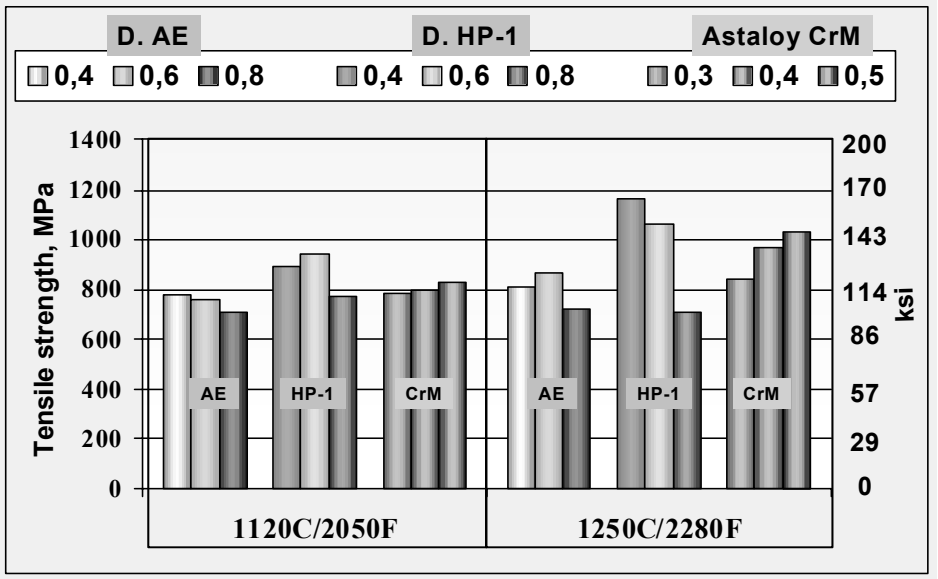


Fig 3. Tensile strength of D. AE, D. HP-1 and Astaloy CrM after sintering at 1120°C/2050°F and 1250°C/2280°F

Elongation

The telongation achieved for the three materials at the different carbon contents are shown in fig 4 below. As can be seen the elongation increased substantially for the Astaloy CrM when the sintering temperature was increased to1250°C/2280°F. At this sintering temperature elongation of 3,4% was obtained at the lower carbon content of 0,3%. At the higher carbon content levels 0,4 and 0,5% the elongation dropped to 2,6 and 1,5 % respectively. Combined with the high tensile strength levels of close to 1000 MPa / 143 ksi this is an exceptionally good combination of mechanical properties after sintering.

The two diffusion alloyed materials achieved a decrease in elongation with the increase in sintering temperature except for the D. HP-1 material at the low carbon content of 0,4%. This decrease is related to the increase in hardness shown below.

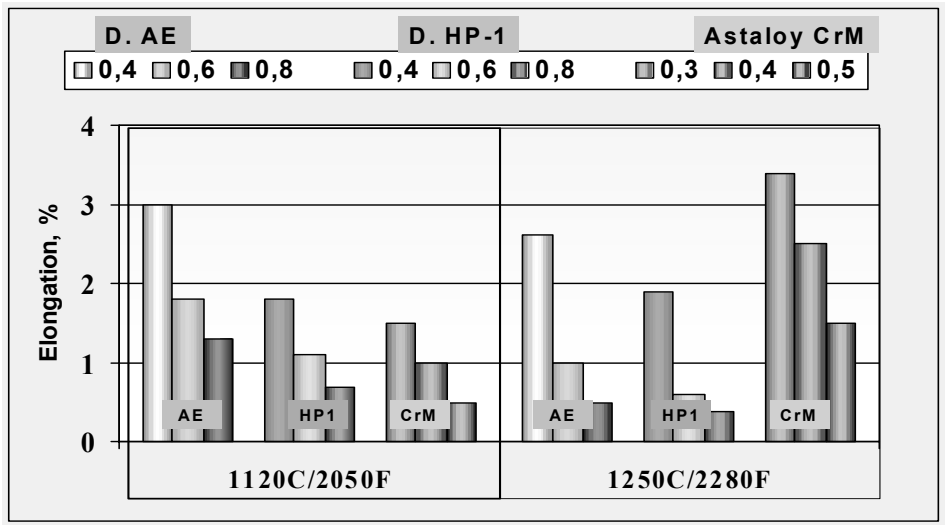


Fig 4. Tensile strength of D. AE, D. HP-1 and Astaloy CrM after sintering at 1120°C/2050°F and 1250°C/2280°F

Hardness, HV10

The macro hardness HV10 obtained with the three different materials are shown in fig 5 below. It can be seen that all materials obtained increased hardness except Astaloy CrM at the highest carbon level of 0,5%. D. HP-1 reached the highest hardness when the sintering temperature was increased. At this temperature hardness levels in the range of 450-500 was obtained. The hardness of the D. AE material also increased substantially for the two higher carbon contents. The Astaloy CrM material only showed a slight increase at the two lower carbon content levels.

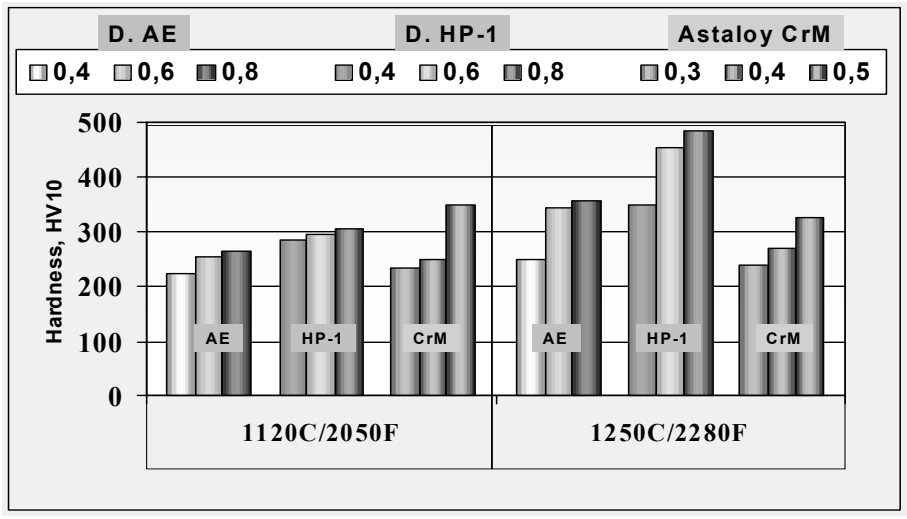
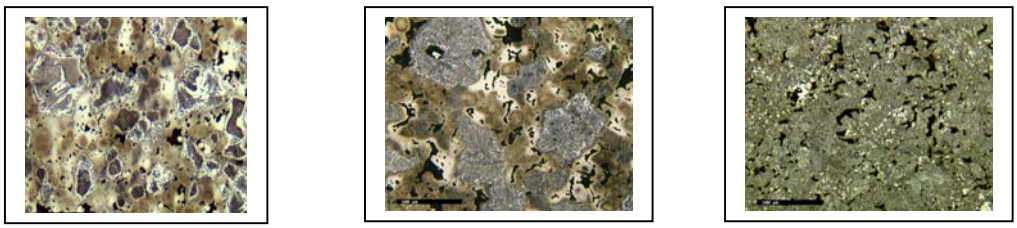


Fig 5. Hardness, HV10, of D. AE, D. HP-1 and Astaloy CrM after sintering at 1120°C/2050°F and 1250°C/2280°F

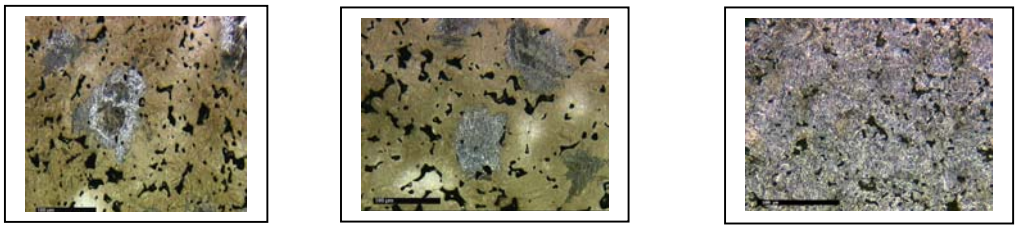
Microstructures

The microstructures obtained for the three different materials at their medium carbon content are shown in fig 3A-C after sintering at the 1120C/2050F and in fig 4A-C for the materials sintered at 1250C/2280F..



3A: D. AE 3B: D. HP-1 3C: Astaloy CrM

Fig 3A-C. Microstructure obtained for D. AE, D. HP-1 and Astaloy CrM after sintering at 1120C/2050F for 30 minutes.



4A: D. AE 4B: D. HP-1 4C: Astaloy CrM

Fig 4A-C. Microstructure obtained for D. AE, D. HP-1 and Astaloy CrM after sintering at 1250C/2280F for 60 minutes.

As can be seen the two diffusion alloyed materials have a heterogeneous microstructure containing pearlite, bainite, martensite and nickel rich austenite and ferrite in the case of D. AE after sintering at both temperatures. The Astaloy CrM material achieved a homogeneous microstructure consisting mainly of bainite and some martensite at oth temperatures.

Influence of tempering

The materials sintered at 1250°C/2280°F were also tempered at 200°C/390°F for 60 minutes in air. The result of this treatment regarding tensile strength is shown in fig 5.

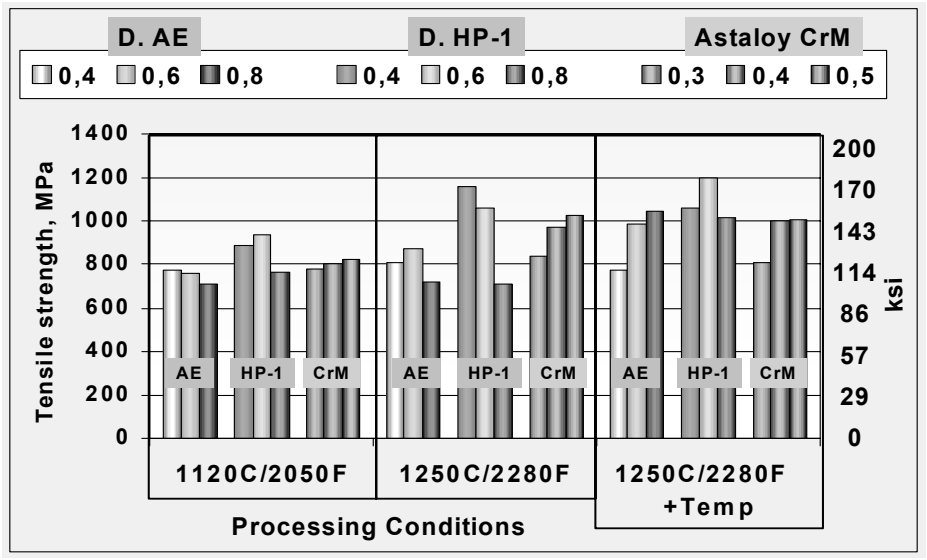


Fig 5. Tensile strength of D. AE, D. HP-1 and Astaloy CrM

As can be seen the tempering treatment had a significant effect on the tensile strength for the D.AE and D. HP-1 materials at the higher carbon content levele. Especially at the highest carbon level 0,8 % the tempering operation has a very strong effect on these two materials. Regarding Astaloy CrM the effect is only minor.

The result of the tempering treatment on elongation is shown in fig 6. Also in this case the tempering treatment had the strongest effect for the D. AE and D. HP-1 materials. Especially at the higher carbon levels the tempering operation has a significant effect on both materials. For both the D. AE and D. HP-1 at carbon content of 0,6 and 0,8% the elongation is increased about 1,0 %. Regarding Astaloy CrM the effect is small.

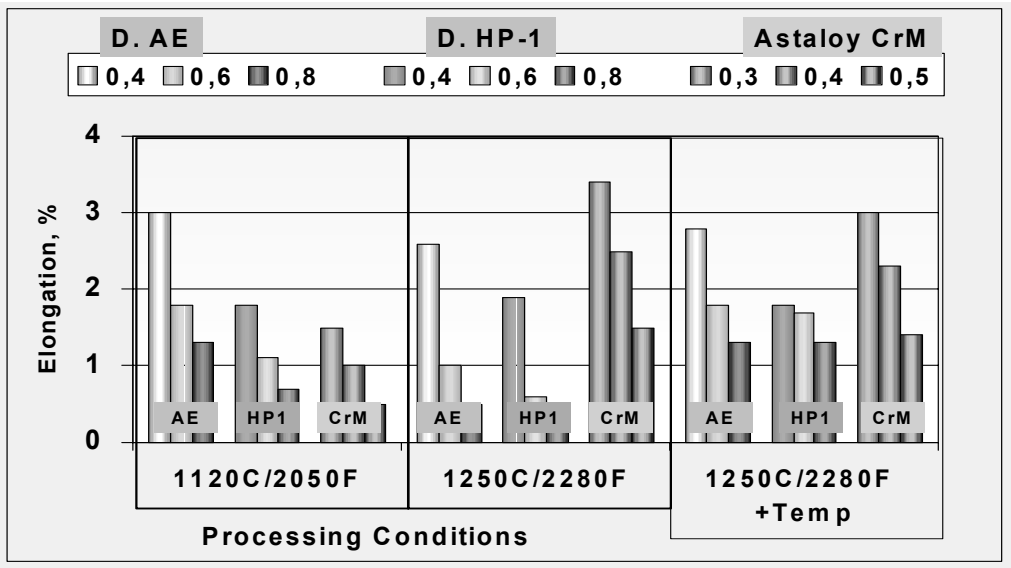


Fig 6. Elongation of D. AE, D. HP-1 and Astaloy CrM after different processing

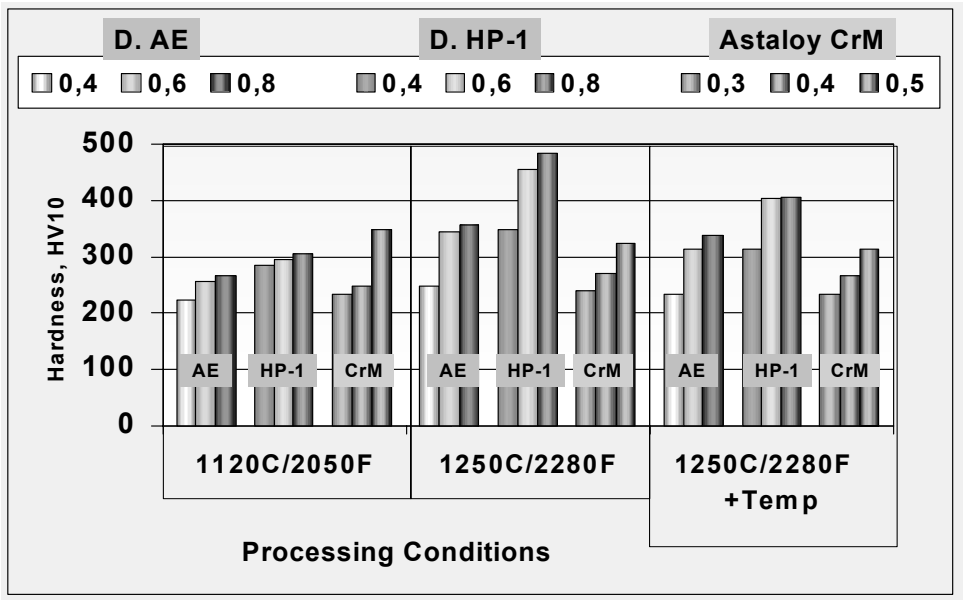


Fig 7. Hardness of D. AE, D. HP-1 and Astaloy CrM obtained after different processing

The effect of the tempering on hardness is shown in fig 7. It can be seen that the tempering treatment had strong effect on the hardness of both the D.AE and D. HP-1 materials at the two higher carbon levels. The decrease in hardness correlate well with the increase in both tensile strength and elongation described above. Regarding Astaloy CrM there is no effect observed.

SUMMARY OF USING INCREASED SINTERING TEMPERATURE

The effect of using a higher sintering temperature than 1120°C / 2050°F on mechnical properties is clear from the previous results. In order to show the effect on both tensile strength and elongation at the same time the results obtained for Astaloy CrM at the three different carbon contants are plotted in fig 8 below.It can be seen that by increasing the sintering temperature from 1120°C / 2050°F to1250°C / 2280°F the tensile strength increased for all carbon contents. For the material with the lowest carbon content tensile strength increased from 745 MPa/105 ksi to 800 MPa/ 114 ksi. At the

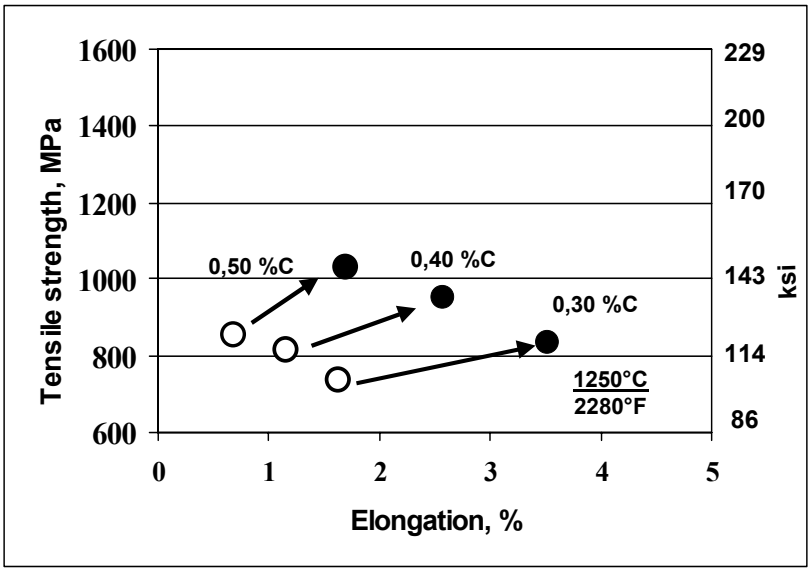


Fig 8. Effect of sintering temperature on properties of Astaloy CrM.

same time the elongation increases from about 1,5% to about 3,5%. At a carbon content of 0,4% the tensile strength went from 800 MPa/ 114 ksi at the lower sintering temperature to 940 MPa/ 134 ksi after sintering at the higher tmperature. The elongation increased from 1% to 2,5%. At 0,5% carbon the tensile strength increased from 875 MPa/ 125 ksi to 1030 MPa/ 147 ksi while the elongation increased to 1,5%.

INFLUENCE OF WARM COMPACTION

The three different powders D. AE, D. HP-1 and Astaloy CrM were also warm compacted in order to study the influence of increased sintering temperature on specimens at increased green densities. The processing carried out is shown in fig 8 below. The powders used with warm compaction were prepared as Densmix™ powders (1). Densmix™ is the trade name for powder mixes for warm compaction offered by Höganäs AB, Sweden.

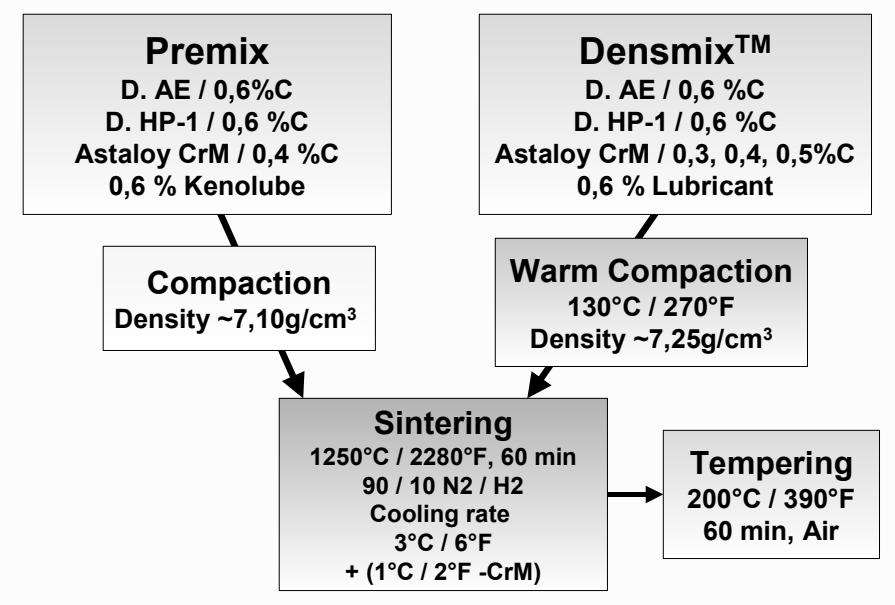


Fig 8. Processing conditions used with warm compaction

For D. AE and D. HP-1 a carbon content of 0,6% was used. For Astaloy CrM a carbon content of 0,4% was tested. Sintering was carried out at 1250C/2280F for 60 minutes.The cooling rate used was 3ºC/s (6ºF/s). Some of the faster cooled specimens were tempered at 200ºC / 390ºF for 1 hour in air. Astaloy CrM was also tested with 0,3, 0,4 and 0,5% carbon using a lower cooling rate, 1ºC/s (2ºF/s) after sintering. In this case no tempering was carried out.

Mechanical properties

The mechanical properties for D.AE, D.HP-1 with 0,6%C and Astaloy CrM with 0,4%C after cold and warm compaction and sintering at 1250°C / 2280°F are shown in fig 9 below.
It can be seen that the three materials reached a higher tensile strength after warm compaction due to increased density. All three materials also obtained higher tensile strength compared to the results described in the previous paragraph. This is due to the increased cooling rate used here 3°C/s (6°F/s) compared to 1°C/s (2°F/s) used previously.

Astaloy CrM achieved the highest tensile strength after both cold and warm compaction and reached a tensile strength of more than 1200 MPa / 140 ksi at a carbon content of 0,4%. This high strength level is due to increased cooling after sintering converting the microstructure to

martensite. The results obtained after tempering are shown in fig 10. As can be seen all three warm compacted materials achieved a substantially higher tensile strength after tempering. The highest tensile strength, 1425 MPa / 150 ksi was obtained with Astaloy CrM.

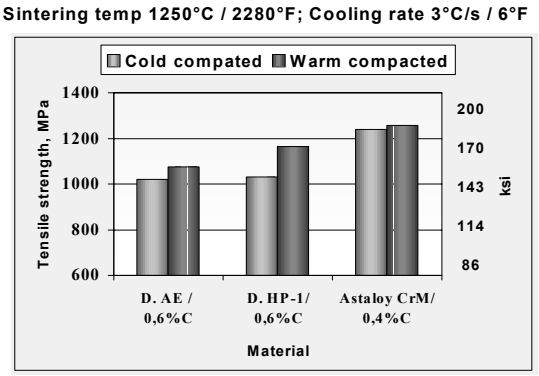


Fig 9. Tensile strength obtained for different PM materials after cold and warm compaction and sintering at 1250C/2280F.

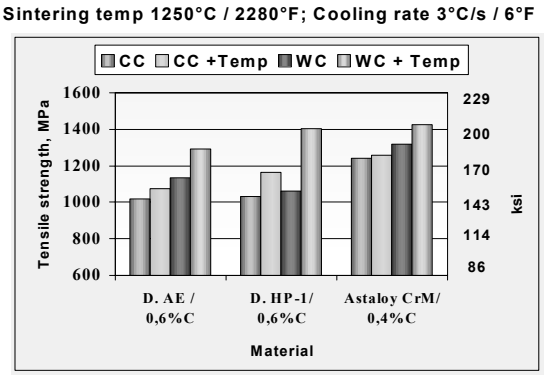


Fig 10. Tensile strength obtained for different PM materials after cold and warm compaction and sintering at 1250C/2280F and tempering.

The elongation obtained for the different materials after cold- and warm compaction, sintering and tempering is shown in fig 11. The elongation was improved for all materials after tempering. The highest elongations were obtained for the warm compacted and tempered materials. D. AE showed the highest values of about 2 %. It is worth to point out the outstanding combination of tensile strength, 1425 MPa / 150 ksi and 1,5% elongation reached with the Astaloy CrM material.

The hardness obtained is presented in fig 12. As expected all materials show a decreased hardness level after tempering. The smallest effect is obtained for Astaloy CrM.

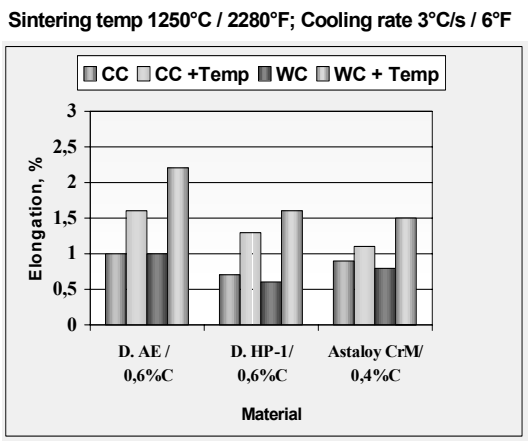


Fig 11. Elongation obtained for the three materials after cold and warm compaction, sintering at 1250C/2280Fand tempering.

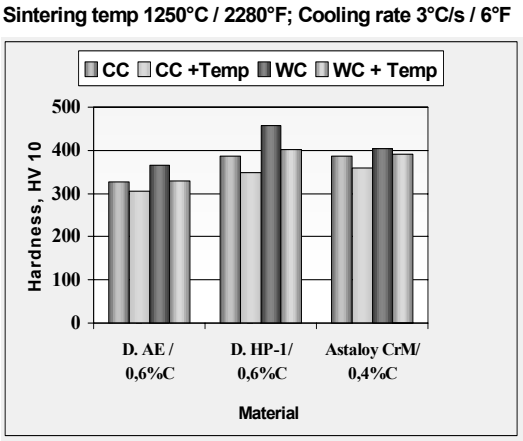


Fig 12. Hardness obtained for the three materials after cold and warm compaction, sintering at 1250C/2280F and tempering.

Warm compacted Astaloy CrM with 0,3, 0,4 and 0,5% carbon respectively were also cooled after sintering at 1250ºC/2280ºF a lower rate of 1°C/s (2°F/s). The resulting tensile strengths and elongations are shown in fig 13 which summarises the effect of warm compaction and sintering temperature on the properties of Astaloy CrM at the three different carbon contents.

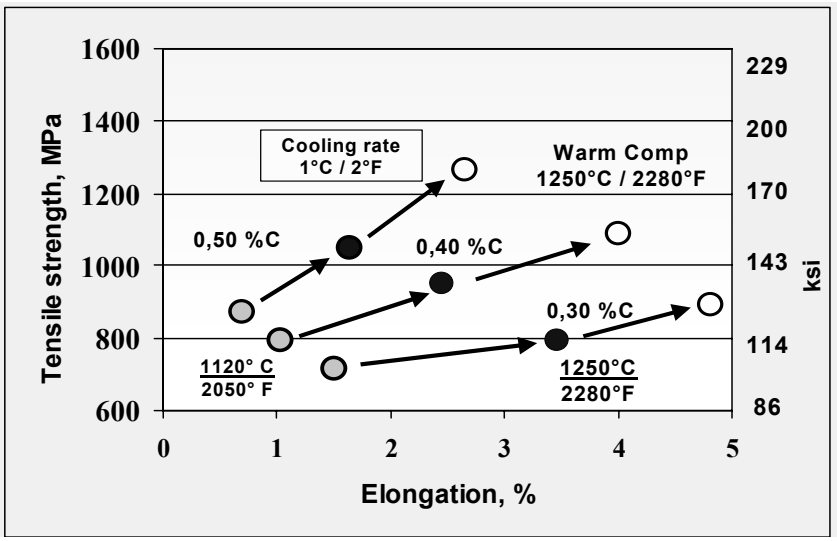


Fig 13. Effect of sintering temperature and warm compaction on properties of Astaloy CrM at a cooling rate of 1ºC/s (2ºF/s)

It can be seen that by increasing the sintering temperature from 1120°C / 2050°F to1250°C / 2280°F the tensile strength increased for all carbon contents. For the material with the lowest carbon content tensile strength increased from 745 MPa/105 ksi to 800 MPa/ 114 ksi. At the same time the elongation increases from about 1,5% to about 3,5%. At a carbon content of 0,4% the tensile strength went from 800 MPa/ 114 ksi at the lower sintering temperature to 960 MPa/ 137 ksi after sintering at the higher tmperature. The elongation increased from 1% to 2,5%. At 0,5% carbon the tensile strength increased from 875 MPa/ 125 ksi to 1060 MPa/ 151 ksi while the elongation increased to 1,5%.

By combining warm compaction with sintering at the higher temperature of 1250°C / 2280°F the properties were improved further. As can be seen this combination of processing resulted in an increased tensile strength of 1100 MPa/ 157 ksi combined with an elongation close to 4% for the material containing 0,4% carbon. For the material with 0,5% carbon the tensile strength increased from 1060 MPa/ 151 ksi to 1270 MPa/ 181 ksi. At the same time the elongation increases from about 1% to about 2,5%. These results show that by combining warm compaction with sintering at high temperature unique combinations of properties can be obtained with Astaloy CrM after sintering which have not been seen in PM before.

The diagram in fig.14 below summarises all the different processing means discussed in this presentation for the Astaloy CrM material with a carbon content of 0,4% C. By selecting a processing route of warm compaction, sintering at 1250°C / 2280°F and using a cooling rate of 3°C/s / 6°F/s a tensile strength of 1350 MPa/193 ksi with an elongation of about 1% can be obtained. By applying a tempering operation the tensile strength can be increased further to 1450 MPa / 207 ksi and with an improved elongation close to 2%. This shows the potential to reach properties with PM materials that never have been possible to obtain in a cost effective way before.

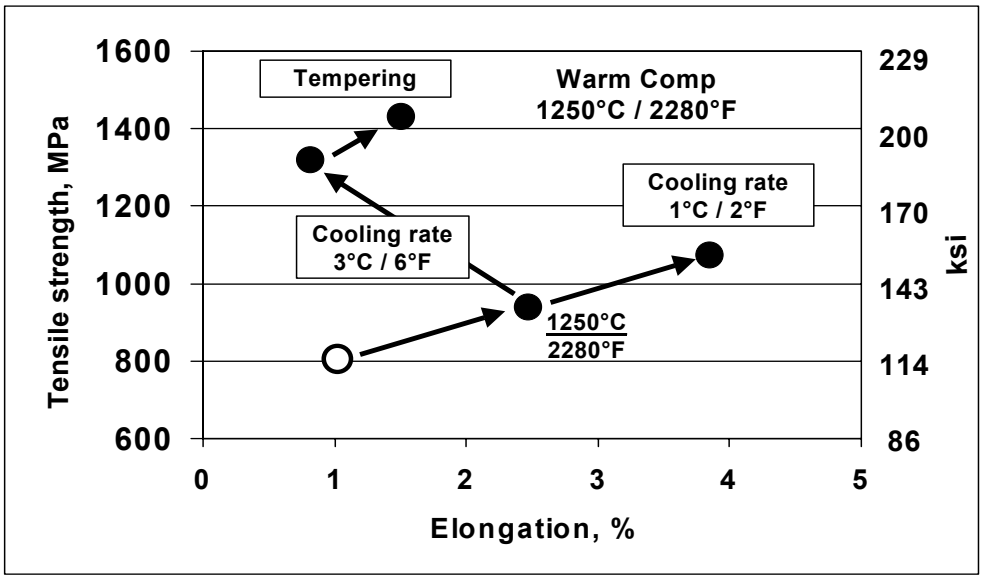


Fig 14. Influence of different processing means on tensile strength and elongation of Astaloy CrM / 0,4%C

CONCLUSIONS

Sintering at a temperature of 1250°C / 2280°F of partially pre-alloyed powders(D. AE), fully pre-alloyed powders (Astaloy CrM) and powders based on combinations of these two alloying methods (D. HP-1) show the following results:

- 10-20 % increase in tensile strength compared to sintering at 1120°C/2050°F

- tensile strength levels ranging from 800-1150 MPa can be obtained

- 100 % increase of the elongation for the Astaloy CrM material

- tempering has a large effect on D. AE and D. HP-1 at carbon contents in the range 0,6-0,8%

- combined with warm compaction tensile strength levels 1000-1250 MPa (143-186 ksi) were obtained

- unique combinations of tensile strength and elongation can be reached with Astaloy CrM in combination with warm compaction: @ 0,4%C: 1100 MPa (157ksi) - 4% elongation
@ 0,5%C: 1330 MPa (190ksi)- 2,7% elongation

- in combination with warm compaction, increased cooling rate and tempering Astaloy CrM obtained a tensile strength of > 1400 MPa (200ksi) with an elongation of ~2%

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