Means to Lift Mechanical Properties to the Next Level, Enabling New Challenging Applications

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ABSTRACT

Distaloy AQ is a rather new material suitable for heat treatments, whereas the new Astaloy CrA and Astaloy CrM are materials suited for sinter hardening. By combining these with warm compaction, mechanical properties can be lifted to the next level, due to increased density and improved pore morphology. This has a positive effect on all mechanical properties, especially properties such as impact energy and fatigue strength. These improved properties open up further potential to convert, challenging conventionally produced parts, such as helical gears and connecting rods to PM-technology.

INTRODUCTION

The continued expansion of the PM market into new applications requires cost-effective materials with increased performance. This can be achieved by different means. The development of new-cost effective alloy systems, new compaction techniques enabling higher densities, sintering combined with increased cooling rates and carbon control and adoption of secondary heat treatments are all examples of means that either singly or in combination can be used to increase material performance.

Alloying elements commonly used in PM materials intended for heat treatments are copper, nickel and molybdenum. However, the raw material prices of these elements have been volatile in recent years, making material cost predictions difficult. Distaloy AQ is a new lean diffusion alloyed powder designed for manufacturing of heat treated high-performance PM components. The low alloy content makes it less sensitive to future price fluctuations and the diffusion alloying concept enables high compressibility combined with consistent robust and economical mass production of components.

Chromium is interesting as a pre-alloying element due to its performance enhancing ability and cost effectiveness. New pre-alloyed Cr containing powders in combination with sinter hardening the advantages of chromium can be fully utilized enabling cost effective manufacturing of new challenging applications for PM.

The objective of this paper is to demonstrate properties achievable with a new lean Ni-Mo diffusion alloyed powder, Distaloy AQ, and two Cr pre-alloyed powders. After different processing routes, materials based on these powders exhibit properties suitable for synchronizing hubs, cam lobes, gears and other challenging applications.

EXPERIMENTAL PROCEDURES

Material

Three different base powders have been evaluated in this study. For sintering and heat treatment the lean diffusion alloyed powder Distaloy AQ has been selected and for sinter hardening, the two pre-alloyed chromium-containing materials, Astaloy CrA and Astaloy CrM. The compositions of the base powders can be found in table 1.

Table 1. Composition of tested base powders

Base powder	Nickel, %	Molybdenum, %	Chromium, %
Distaloy AQ	0,5	0,5	-
Astaloy CrA	-	-	1,8
Astaloy CrM	-	0,5	3,0

The Distaloy AQ was tested at two different graphite levels. A lower, 0,2 %, suitable for case hardening and a higher, 0,6 %, suited for through hardening. The Astaloy CrA needs an addition of copper or nickel to take hardening under typical sinter hardening conditions, whereas the Astaloy CrM takes hardening as

it is. For room temperature compaction (RT), conventional Premixes with 0,8 % Amide-wax were used, whereas the warm compaction has been done with Densmix powders tailored for this purpose. The additives used were fine synthetic graphite, Timcal F10, atomized copper powder -100 mesh and fine carbonyl nickel powder, Inco 123. For complete compositions, see table 2.

Table 2. Composition of test mixes and sintered C-contents of RT and warm compacted materials

Base powder	% Cu -100 mesh	% Ni Inco 123	% Graphite F10	% Lubricant Premix / Densmix	% C sintered RT / Warm
Distaloy AQ	-	-	0,20	0,8 / 0,6	0,17 / 0,16
Distaloy AQ	-	-	0,60	0,8 / 0,6	0,58 / 0,56
Astaloy CrA	1,0	-	0,65	0,8 / 0,6	0,63 / 0,58
Astaloy CrA	-	2,0	0,60	0,8 / 0,6	0,56 / 0,56
Astaloy CrM	-	-	0,50	0,8 / 0,6	0,46 / 0,44

Processing and evaluation

Tensile, impact and fatigue test specimens according to ISO-standards were compacted using a 60-ton hydraulic compaction press at a fixed compacting pressure of 700 MPa. This was done at room temperature (RT) for the Premixes and with powder as well as die heated to 120°C for the Densmixes (warm). Additionally, gear specimens with an outer diameter of 32 mm were compacted, see figure 1 for details.

Gear data
Teeth number z = 18
Module m_n = 1,5875 mm
Pressure angle α_n = 20°
Face width b = 10 mm
Outer diameter $Ø_o$ = 32 mm



Figure 1. Gear data for gear specimens used for tooth root bending fatigue testing.

All test specimens were sintered in a mesh belt furnace at 1120ºC for 20 minutes in a 90/10 N_2/H_2 atmosphere with carbon potential. The cooling rate for the conventional sintering was approximately 1ºC/s and for the sinter hardening approximately 3ºC/s. The through hardening of Distaloy AQ was done at a temperature of 860°C where the specimens were kept for 20 minutes at a C-potential of 0,6 %. The case hardening was done at the same conditions, except for a higher C-potential of 0,8 %. Both the sinter hardened and heat treated specimens were tempered at 200ºC for 60 minutes in air for stress relief.

Plane bending fatigue was tested at R=-1 and with a run out limit of $2x10^6$ cycles using the staircase method according to MPIF Standard 56. The endurance limit was determined at 50 % survival. The tooth root bending fatigue was done on the gear seen in figure 2, by applying a force on the tooth tips. Tests were made at R=0,1, using the stare case method, with a run out limit of $3x10^6$ cycles. The stress evaluation was done according to ISO 6336.

RESULTS

Powder properties, Distaloy AQ

Warm compaction technology was introduced in 1994 [1]. This is a technique in which a bonded mix with special organic additives is used in order to be able to fill the powder which is heated to 120°C, into a die that is also heated to 120°C. The special mix type, in combination with the elevated temperature, increases the green density but, especially the green strength (figure 2). The green density is increased by almost 0,2 g/cm^3 by applying warm compaction to a mix containing Distaloy AQ with an addition of 0,6 % of both graphite and lubricant. The corresponding green strength is increased by 65 %, reaching levels

of 20 N/mm^2. The increase in density remains after sintering and results in improved mechanical properties.

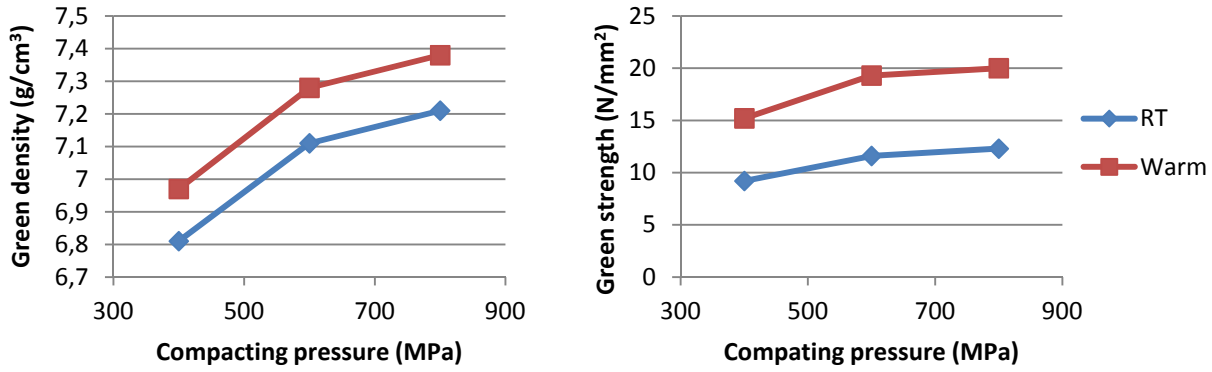


Figure 2. Green density and green strength of Premix powders for room temperature (RT) compaction and Densmix powder for warm compaction containing Distaloy AQ + 0,6 % graphite + 0,6/0,8 % lubricant.

Mechanical properties of sintered and heat treated material

The apparent hardness (HV10) of the sintered Distaloy AQ specimens is in the range of 100-150 with the higher numbers indicating higher carbon content. This rather low level facilitates sizing and coining after sintering when applicable. Hardness levels of 380 and 405 are achieved after through hardening for RT- and warm compacted materials respectively. The corresponding values after case hardening are even higher at 441 and 475 (figure 3). For the heat treated materials, higher hardness levels are seen for warm compacted materials.

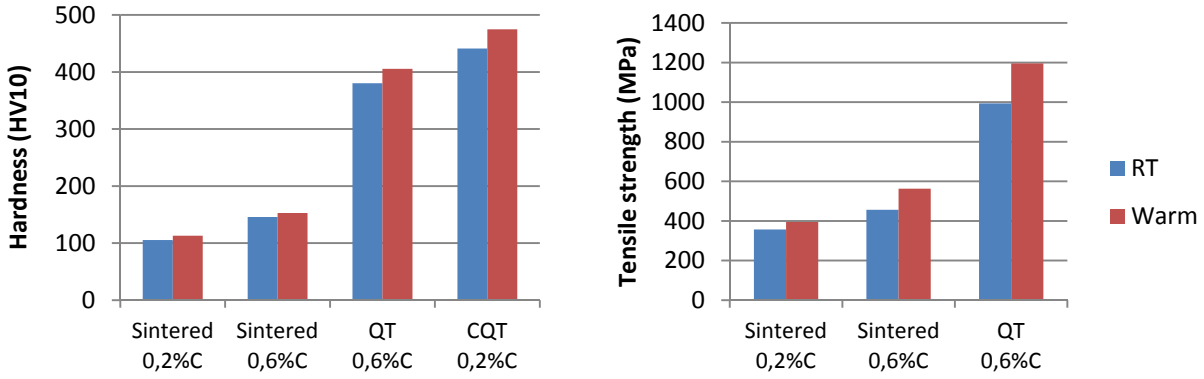


Figure 3. Vickers hardness and tensile strength of Distaloy AQ with 0,2 % and 0,6 % graphite added compacted conventionally at room temperature or with warm compaction after sintering, through hardening (QT) and case hardening (CQT).

Sintered tensile strength varies in the range of 260 to 560 MPa with increasing numbers for warm compaction and higher carbon contents. Warm compaction has an even larger effect on the through hardened material, increasing tensile strength from 1000 MPa to 1200 MPa.

Warm compaction also has a positive effect on ductility of the materials, here evaluated as impact energy. This applies especially in the sintered condition at a carbon content of 0,2 %. With conventional compaction impact energy of 49 J is achieved, see figure 4. By applying warm compaction it is increased by 60 % to 80 J. At the higher carbon content of 0,6 % the increase is as much as 70 %, but starting at a lower level of 18 J going up to 31 J. This increase is an effect of the higher sintered density, which is very critical for impact energy. When other mechanical properties increase more or less linearly with density,

impact properties improve more rapidly at higher densities. After heat treatment, the impact energy is quite low at 12-13 J for all four materials. This is probably an effect of the very high hardness levels.

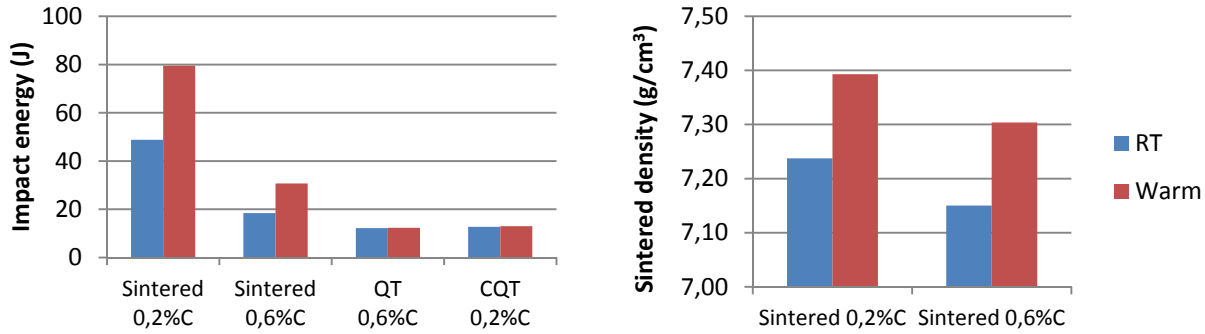


Figure 4. Impact energy of Distaloy AQ with 0,2 % and 0,6 % graphite added compacted conventionally at room temperature or with warm compaction after sintering, through hardening and case hardening together with the corresponding sintered densities.

The plain bending fatigue strength was evaluated for through and case hardened materials. By applying warm compaction there is a small increase for the through hardened material, see figure 5. The case hardened material shows an increase of more than 20 % by using warm compaction, reaching values above 500 MPa for the fatigue limit at 50% survival. The trend is the same for the tooth root bending fatigue measured on the gears. Here, a fatigue limit of more then 700 MPa is achieved when combining warm compaction and case hardening of Distaloy AQ.

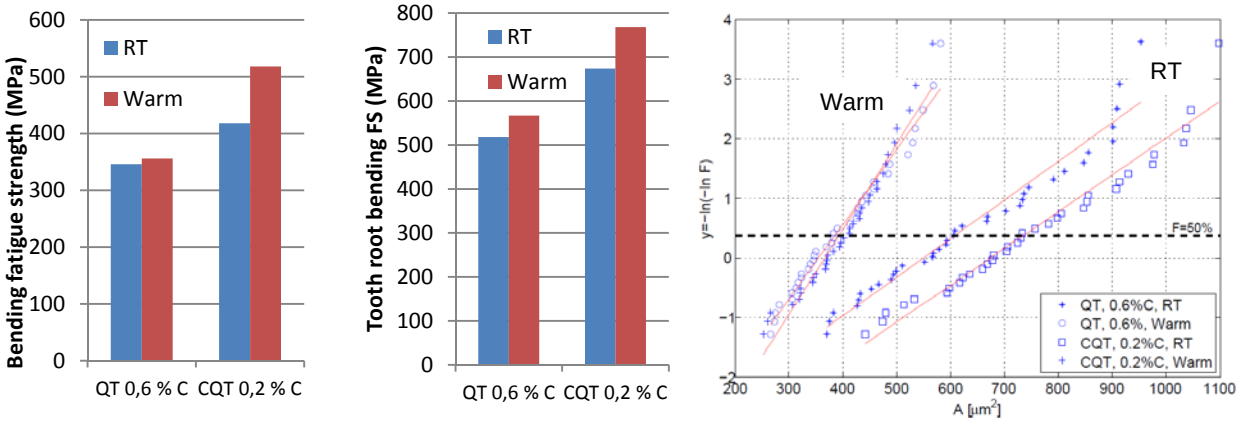
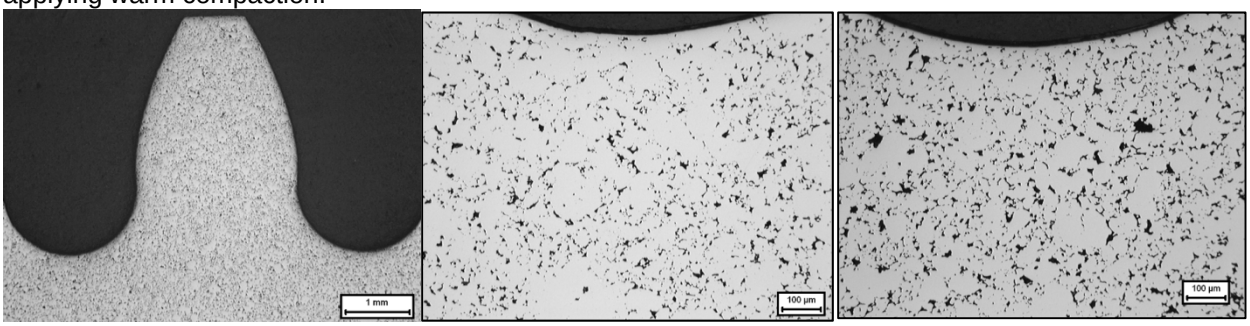


Figure 5. Plane bending and tooth root bending fatigue strength of conventionally and warm compacted Distaloy AQ in the through hardened and case hardened condition together with maximum pore size measurements and Gumbel distributions of the four materials.

Metallography of sintered and heat treated material

The porosity was investigated, looking at the un-etched structures in the tooth root area. It is assumed that the fatigue crack starts at the largest pore in the stressed area, which is why the largest size of the pores has been determined for a large number of fields. These are plotted in figure 5, far right, expressed as the pore area on the x-axis and the probability, F, of occurrence on the y-axis. The red lines represent the Gumble distributions that delineate the largest pore size distributions. Here, it can be seen that the warm compacted materials, the two lines to the left, have smaller largest pores and a more narrow distribution of the largest pore. This, especially the smaller largest pore size, is very beneficial for the fatigue strength. This correlation has previously been investigated in reference 2.

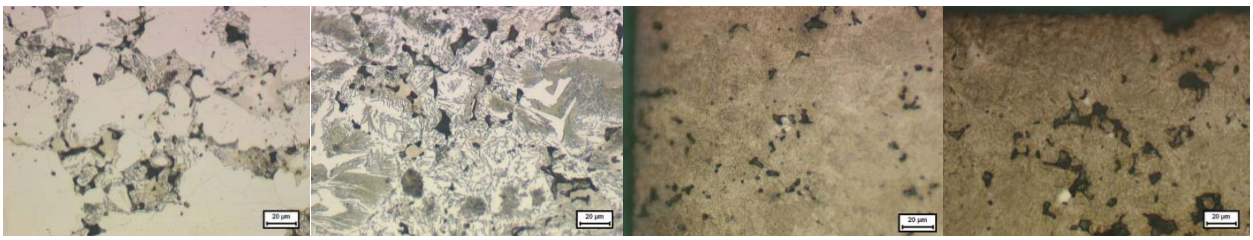
The difference in pore size distribution can also be seen in the un-etched microstructure in figure 6. Figure b shows a warm compacted tooth root compared to a room temperature compacted tooth root in figure c. In addition it is possible to see here that both average porosity and largest pore size are smaller when applying warm compaction.



a) *b)* *c)*

Figure 6. Un-etched microstructures of case hardened gears made of Distaloy AQ + 0,2 % C; a) warm compacted teeth, b) warm compacted tooth root and c) room temperature compacted tooth root.

The etched samples show that the sintered Distaloy AQ with 0,2 % C is mainly ferritic with some perlitic areas, mainly around the original particle boundaries (figure 7). By increasing carbon content to 0,6 %, the material becomes more perlitic with well-distributed ferritic areas. The through hardened material is fully martensitic with some small Ni-rich austenitic areas both at the surface and in the centre. The case hardened material shows the same structure at the surface as the through hardened material, whereas the centre consists of martensite, perlite, ferrite and Ni-rich austenite. The micro hardness at the surface was measured to HV0,1=700. This explains why data are lower compared to earlier trials [3], where the surface hardness was HV0,1=800 and the corresponding tensile and fatigue data some 10 % higher.



a) b) c) d)

Figure 7. Etched microstructures of Distaloy AQ; a) sintered 0,2 % C at centre , b) sintered 0,6 % C at centre, c) through hardened 0,6 % C at surface and d) case hardened 0,2 % C at surface

Mechanical properties of sinter hardened material

The chromium pre-alloyed powders were selected for sinter hardening. These materials show a good response to warm compaction with increased sintered densities in the range of 0,15 g/cm^3. For Astaloy CrA + 2 % Ni this leads to a sintered density of 7,25 g/cm^3 (figure 8). The increased density results in increased tensile properties. For conventional compaction tensile strength is in the range of 1060-1160 MPa. This increased to 1190-1260 MPa when warm compaction is applied, with the highest values for Astaloy CrA + 2 % Ni.

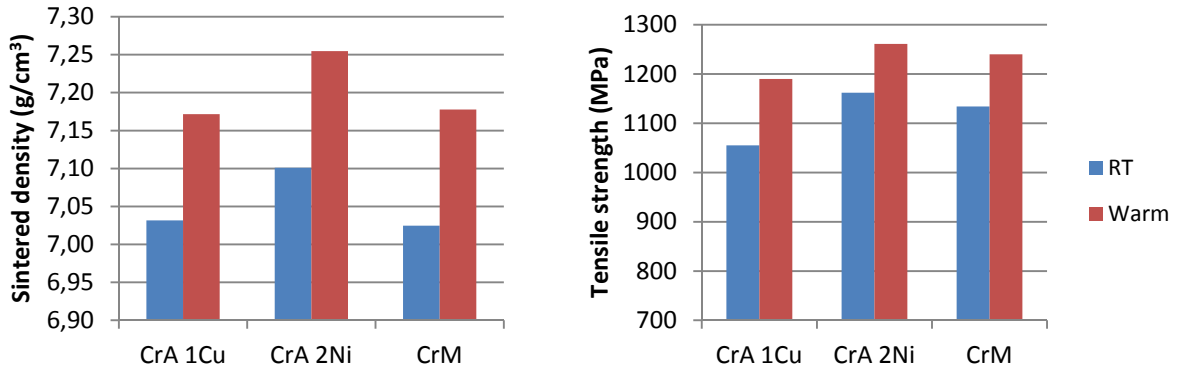


Figure 8. Sintered density and tensile strength of conventionally and warm compacted Astaloy CrA with Cu or Ni added and Astaloy CrM in the sinter hardened and tempered condition.

Hardness and fatigue strength follow the same pattern as the tensile strength. The warm compacted hardness values vary between 408 to 425 HV10, see figure 9. The plane bending fatigue strength shows the largest increase for the Astaloy CrA + Cu, whereas the warm compacted Astaloy CrA + 2 % Ni shows the highest fatigue strength, 379 MPa at 50 % survival. The fatigue strength can be increased further by applying a C-potential during sintering, resulting in a C-gradient with higher C-content at the surface. This leads to compressive stresses as well as higher hardness at the surface which is very beneficial for the fatigue strength, raising it by 90 MPa to 448 MPa. The Astaloy CrM is lower at 363 MPa.

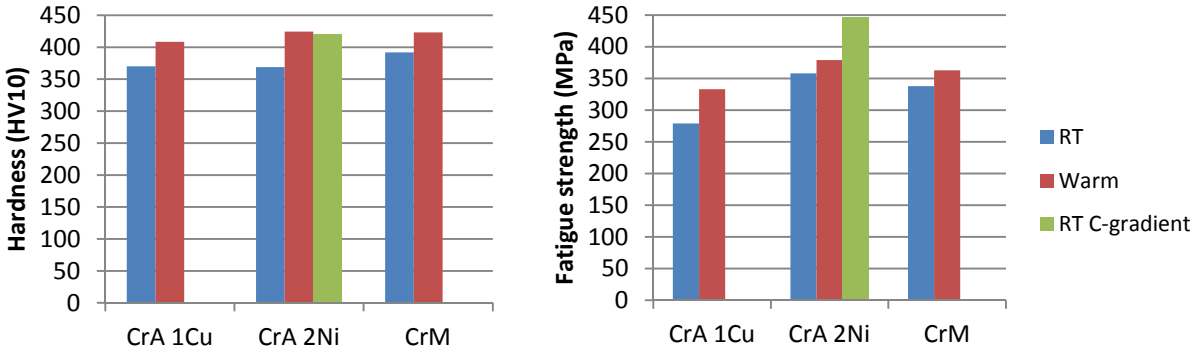
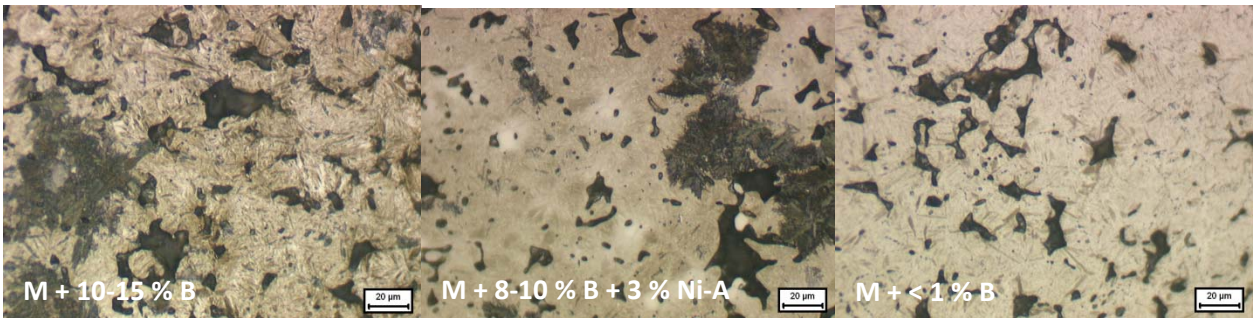


Figure 9. Vickers hardness and plane bending fatigue strength of conventionally and warm compacted Astaloy CrA with Cu or Ni added and Astaloy CrM in the sinter hardened and tempered condition.

Metallography of sinter hardened material

High hardness and corresponding high mechanical properties is an effect of the high amount of martensite in the microstructure after sinter hardening and the higher density of the warm compacted materials.



a) *b)* *c)*

Figure 10. Etched microstructures of conventionally compacted, sinter hardened and tempered; a) Astaloy CrA + 1 % Cu, b) Astaloy CrA + 2 % Ni and c) Astaloy CrM

CONCLUSIONS

- Warm compaction increases green strength by 65 % and green density by 0,15-0,2 g/cm^3.
- The increased density has a positive effect on both strength and ductility.
- Warm compaction decreases the size of the largest pores, which improves fatigue strength.
- A plane bending fatigue strength of 447 MPa can be achieved by warm compacting Astaloy CrA + 2 % Ni + 0,6 % gr and sintering with a C-potential, giving a C-gradient.

REFERENCES

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