NEW HIGH PERFORMANCE PM APPLICATIONS BY WARM COMPACTION OF DENSMIX POWDERS

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,Abstract: To increase the competitiveness of PM compared to other manufacturing techniques there is a demand for alloy systems as well as processes which result in improved mechnical properties with maintained precision of tolerance control at reduced processing costs. Warm compaction was developed to be one possible technique to meet this objective. By warm compaction of low alloy steel it has now become possible to produce PM parts with uniform densities up to 7.4 g/cc by single compaction and sintering. The higher and more even density results in improved static and dynamic mechanical properties. However, warm compaction not only improves the static mechanical properties which opens up new opportunities to use PM in high performance applications that up to now have not been technically and economically feasible.

In this paper some of the merits that have been found with warm compaction both in laboratory scale and in production of complex parts are described. Material properties and process robustness obtained with warm compaction of Densmix powders are presented. Future potential high performance applications that might be realised by utilising the merits of warm compaction of Densmix powders will be discussed.

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. Higher densities than the range currently produced (6.5- 7.2 g/cm3) will in the future be required for more highly stressed applications. As increased density improves mechanical properties in general and dynamic properties in particular it has always been important for the PM industry to find cost effective ways to further improve density of the parts.

The development of high compressible powders has made manufacturing of high density components without using double pressing and double sintering possible. Another development to

achieve higher density that has taken place during the last years is warm compaction [1]. This technology was introduced in the market 1994 and has since then rapidly won ground as a cost effective method to produce high density parts for use in various applications. Over two hundred different components are now in production. The most common parts so far are different kinds of helical gears for hand power tools. Table 1 below shows the actual situation in different market areas. As can be seen warm compaction has become an established production method for different kinds of PM parts. The size of the parts are in the range of 5 to 200 grams in Europe and Asia while in USA there exists production of automotive parts weighing up to 1100 grams.

Market Area	**Europe**	**Asia** **Japan, Taiwan, Korea, China**	**USA**
Heating units installed	23	38	15
Parts in production	12	175	35
Weight range, gram	5-200	5-200	10-1100
Type of parts	Helical gears Bevel gears Safety parts Synchronising rings	Helical gears Bevel gears Spiral gears	Helical gears Bevel gears Turbine hubs

Table 1.World wide situation for warm compaction in July 2000.

Typical examples of components that are being produced by warm compaction are shown in figure 1 and 2 below.



Figure 1. Example of part produced by warm compaction



Figure 2. Examples of parts produced by warm compaction

During the years passed since the introduction of warm compaction a lot of results and experiences have been gained both in laboratories and in production of parts. The benefits that have been found are not only the increase of density, green strength and static mechanical properties but also a number of unexpected factors that will be beneficial to increase the competitiveness of PM. The most important ones are:

- increased density => increased mechanical properties
- increased green strength => green machining
- more even distribution of density => increased tolerances, reduced scatter in properties
- cost savings

PROPERTIES OBTAINED WITH WARM COMPACTION

In order to demonstrate the difference that can be obtained with warm compaction in comparison to the conventional PM process at room temperature specimens using both processes were prepared. The powders and processing conditions used are showed in table 2 below. Green and sintered properties were analysed according to standardised test methods.

Powder	Distaloy AE	Distaloy HP-1	Astaloy CrM
Carbon content, %	0.6	0.6	0,4
Pressing mode	Cold, Warm	Cold, Warm	Cold, Warm
Compacting pressure, MPa Compacting pressure, tsi	600, 800 43, 57	600, 800 43, 57	600, 800 43, 57
Sintering conditions Temperature, ºC / ºF Time, min Atmosphere	 1120 / 2050 30 endogas	 1120 / 2050 30 endogas	 1120 / 2050 30 90/10 N2/H2

Table 2. Powders and processing conditions used to compare properties obtained by warm compaction and conventional compaction.

Distaloy 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. Distaloy 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. The powders that were warm compacted were prepared as Densmix powders. Densmix™ is the trade name for powder mixes for warm compaction offered by Höganäs AB.

Density and green strength

In table 3 a comparison of the green densities obtained for the three powders is shown after warm compaction and conventional compaction at room temperature using a compaction pressure of 600 and 800 MPa. It can be seen that all warm compacted powders achieved higher green densities compared to the mixes compacted at room temperature for both compaction pressures. The increase in green density ranged from about 0,20 g/cc at the lower compacting pressure 600 MPa to about 0,15 g/cc when compacted at 800 MPa.

Powder	Distaloy AE				Distaloy HP-1				Astaloy CrM			
Carbon content, %	0.6				0.6				0,4			
Pressing mode	Cold		Warm		Cold		Warm		Cold		Warm	
Comp. pressure, MPa	600	800	600	800	600	800	600	800	600	800	600	800
Comp. pressure, tsi	43	57	43	57	43	57	43	57	43	57	43	57
Green density, g/cm3	7,11	7,29	7,28	7,42	7,01	7,18	7,19	7,32	6,97	7,16	7,15	7,27
Sintered density,g/cm^3	7,12	7,30	7,29	7,42	7,03	7,19	7,20	7,33	6,99	7,17	7,15	7,28
Green strength, MPa	12	14	28	29	11	15	18	19	10	15	17	18

Table 3. Green density and green strength and sintered density of different powders after warm compaction at 150 C and room temperature.

The highest densities are obtained with the Distaloy AE based Densmix™ powders which is due to the high compressibility of the base iron powder used, ASC 100.29. The Distaloy HP-1 based mixes achieved about 0,10 g/cm^3 lower density than the Distaloy 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 Distaloy HP-1. The green densities obtained with the Astaloy CrM based mixes is slightly lower than for Distaloy HP-1 which is due to the somewhat lower compressibility of the Astaloy CrM base powder due to its higher alloying content.

One important fact to notice is that all powder mixes achieved about the same densities after warm compaction at 600 MPa as the conventional mixes obtained after compaction at 800 MPa. This is valid for all low alloy steel powder mixes independently if they are based on premixes, partially pre-alloyed or fully pre-alloyed powders. This positive effect can be utilised to reduce the compaction pressure required for a given application and thereby reduce the tool wear. Another benefit is the possibilities to utilise a press with a lower compaction pressure range to obtain the desired density.

The densities obtained after sintering are consistent with the green density results shown previously, see table 3. The densities obtained by warm compaction are 0,15-0,20 g/cm^3 higher than those obtained by conventional compaction at the different pressures used. As the dimensional change during sintering is close to zero for all three materials the difference between green and sintered densities is very small at both compacting pressures.

The green strength obtained is considerably higher for the three warm compacted powders than for the conventionally compacted powders. As can be seen from table 3 the green strength has increased more 100 % for the Distaloy AE powder and for the two other powders the increase is about 50-75 %. This increase in green strength opens up possibilities to machine parts already in the green state and thereby reduce the manufacturing costs.

Mechanical properties

The mechanical properties obtained for the three different materials are shown in table 4. Regarding tensile strength it can be seen that it is about 10-20 % higher for all warm compacted materials compared to the conventionally pressed materials at the same compaction pressure.

Powder	Distaloy AE				Distaloy HP-1				Astaloy CrM			
Carbon content, %	0.6				0.6				0,4			
Pressing mode	Cold		Warm		Cold		Warm		Cold		Warm	
Comp. pressure, MPa	600	800	600	800	600	800	600	800	600	800	600	800
Comp. pressure, tsi	43	57	43	57	43	57	43	57	43	57	43	57
Sintered density,g/cm^3	7,12	7,30	7,29	7,42	7,01	7,18	7,19	7,32	6,97	7,16	7,15	7,27
Tensile strength, MPa	745	850	845	920	850	1025	1020	1120	775	875	871	930
Yield strength, MPa	385	410	405	440	530	568	559	585	533	550	548	565
Hardness, HV10	240	284	281	310	260	302	298	325	240	282	280	335
Impact energy, J	25	38	40	53	21	34	34	41	20	24	25	36

Table 4. Mechanical properties of different PM materials after compaction at 150 C and room temperature followed by sintering at 1120 C 30 min

It can also be seen that the tensile strength of the warm compacted materials at 600 MPa compacting pressure is about the same as for the materials obtained from the conventional compacted mixes using a compaction pressure of 800 MPa. This increase is related to the increased density achieved by warm compaction. The highest tensile strength is achieved with Distaloy HP-1, which after warm compaction at 800 MPa reach a strength level of more than 1100 MPa. This strength level is about the same as is normally obtained with Distaloy AE after a heat treatment operation. The Astaloy CrM based material at a carbon content of 0,4 % achieved a slightly higher strength than the Distaloy AE based material containing 0,6% C**.**

Regarding yield strength it can be seen that both Distloy HP-1 and Astaloy CrM materials achieved a considerably higher strength level than the Distaloy AE based material. This is due to pre-alloying with of Mo and Cr / Mo respectively of the base powders which result in a homogenous strengthening of the matrix.

The macro hardness HV10 obtained with the different materials show that very high hardness levels are obtained with especially Astaloy CrM already after sintering despite the fairly low level of carbon content.

Regarding impact energy it can be seen that the materials based on the warm compacted Densmix powders all achieved substantially higher impact energies The highest impact energies are obtained for the two Distaloy materials. The highest levels are achieved for the materials compacted at 800 MPa as these materials obtained the highest density which has a strong influence on this property. The impact energy for the Distaloy AE based material is increased from 25 J to 40 J and from 38 to 53 J when compacted at 600 and 800 MPa respectively.

Fatigue properties

Axial fatigue tests were also carried out with the three different materials. In this study Densmix of the three compositions were compared with conventionally compacted mixes using a compaction pressure of 700 MPa. The carbon content in the materials and the sintering conditions were the same as already described in table 2. Un notched fatigue test bars were tested in axial mode at an R value of -1. The results of these tests are shown in figure 3.

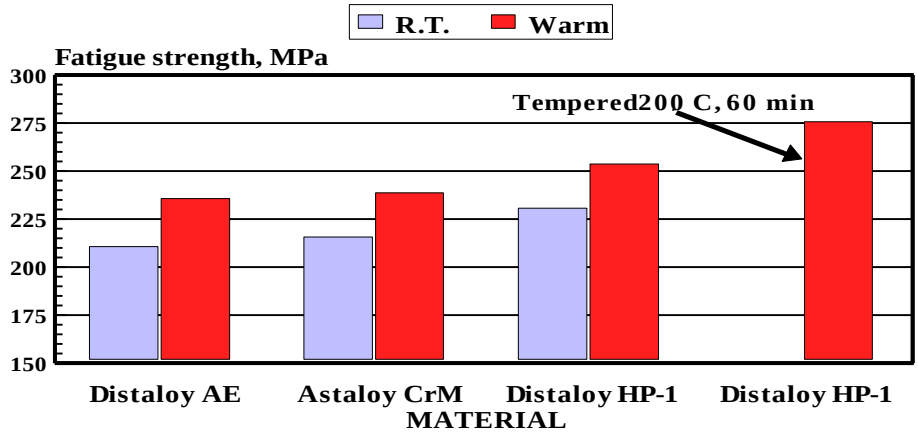


Figure 3: Comparison of axial fatigue strength, (R = -1; Kt =1,0), for different PM materials

As can be seen the materials based on the warm compacted Densmix powders achieved higher fatigue strength compared to the materials compacted at room temperature. The warm compacted Distaloy HP-1 material obtained the highest fatigue strength, 255 MPa, which corresponds to an increase of about 10 %. The warm compacted Distaloy AE based material achieved fatigue strength of 235 MPa which was about 10 % higher than the corresponding cold compacted Distaloy AE material. The Astaloy CrM material reached a fatigue strength of 238 MPa which is slightly higher than the Distloy AE material. All the improvements in fatigue strength are related to the increase in density obtained by warm compaction. It can also be seen that by applying a tempering operation, 200 C for 1h, on the Distaloy HP-1 material the fatigue strength can be increased by about 20 MPa and reach a level of 275 MPa. By increasing the carbon content 0,10% to 0,70% and increase the compacting pressure to 800 MPa axial fatigue strength close to 300 MPa can be obtained with this material. One advantage that has been found with warm compaction is the finer pore size which results in slightly improved

fatigue properties in combination with a decreased scatter compared to conventionally compacted materials [2].

NEWLY DEVELOPED APPLICATION

Synchronising ring

Synchronising parts are to a large extent produced by PM already today but still a large number are produced by conventional steels due to strength reasons. As the mechanical properties can be improved by warm compaction due to the increased density a number of more highly stressed parts will be possible to convert to PM. In the following a synchronising ring successfully converted to PM will be described.

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The synchronising ring, shown in figure 4 below, has a complex shape with high demands on close tolerances combined with high strength . It is used in a 5 gear rear wheel drive gearbox of a small transport truck. The transferred torque is 270 Nm. It has an outer diameter of 92 mm, an inner diameter of 78 mm and a height of 8,5 mm. As the density after compaction can vary consider-ably within the part it can be hard to manufacture in mass production scale with good dimensional tolerances. Therefore, production of this complex part utilising the warm compaction process is a good measure of the capability of this technology.

The synchronising ring is manufactured by warm compaction followed by high temperature sintering and vibration tumbling. Finally a foil is welded to the ring with the purpose to act as wear surface. The powder used is Distaloy AE + 0,5 % graphite prepared as a Densmix™ and is heated in a slot heater. The ring is warm compacted to a density exceeding 7,20 g/cm3 at 6 strokes /minute. The tool is made of high speed steel and equipped with heating device for the die and upper punches. The hardness obtained after sintering exceeds 260 HV10 and makes a secondary heat treatment operation unnecessary. By selection of an appropriate material and utilising warm



Figure 4. Synchronising ring

compaction and it has now been possible to manufacture this complex component successfully by a cost effective single compaction and sintering process with the required hardness and strength.

FUTURE APPLICATIONS

Components, which are now coming more and more into focus are those subjected to heavy fatigue loading. Examples of such components are highly stressed synchronising hubs, rings and cones, different types of gears and cam lobes. The most prominent of those components are connecting rods and transmission gears. The possibilities to realise these components by the conventional PM process are becoming stronger as the mechanical properties of PM steels today are close to those of wrought high strength steels. In the following some ongoing development of new applications for PM is described.

Connecting rod

The increased density obtained with warm compaction brings the fatigue strength to higher levels as previously shown. The high green strength obtained with warm compaction also opens up possibilities to carry out machining in the green state which will contribute to a substantial cost reduction of the finished rod as machining in the green state is substantially more easy then in the sintered state. At the moment several development projects directed towards commercial production of PM connecting rods are going on at many different locations in the world.

The prototype con rod shown in figure 5 below is one example of a development that has been carried out at Höganäs AB [3]. This prototype rod is designed to survive a fatigue load at least 50% larger than the cyclic load on the con rod at engine peak power and still be lighter than the powder forged or forged con rods currently used in the engine. The material used is Distaloy HP-1 with a carbon content of 0,7 %.

The prototypes have been manufactured in a hydraulic press upgraded for warm compaction. Machining of the screw holes and the threads was carried out after compaction whereas the fracture splitting of the big end was performed in the as sintered condition. At the moment finished warm compacted and sintered prototype con rods are under fatigue testing.

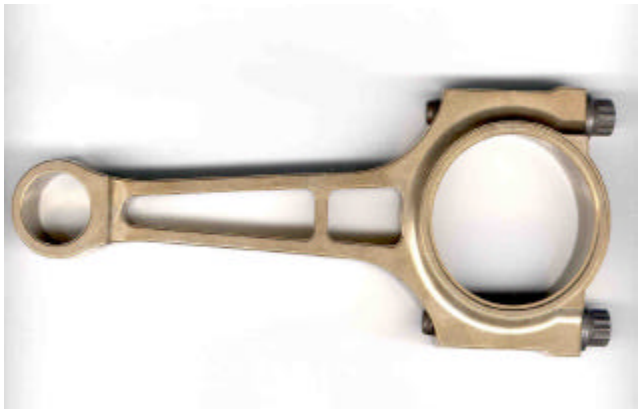


Figure 5. Warm compacted prototype con rod



Figure 6. Synchronising latch cone

Synchronising latch cone

The synchronising latch cone shown in figure 6 is a large part with a weight of 466gram and an outer diameter of ∅180 mm. The cone is used in the gear box of heavy trucks. Up to now this component have been either precision forged or powder forged followed by an induction hardening of the teeth. In a project funded by the Swedish government and carried out under the framework of Jernkontoret this latch cone was selected as a suitable demonstration object [4].

The tool was designed and produced by Werkzeugbau Alvier, Swizerland. Pressing was carried at Dorst in Germany in a new 450 hydraulic press. The parts were warm compacted of a Densmix based on Distaloy AB with 0,5 % graphite UF-4. The compacting pressure used was 640 MPa (40 tsi) at 4 strokes per minute. Sintering was carried out in a belt furnace at 1120 C (2050 F) for 20 minutes in endogas. Induction hardening of the teeth was made in Sweden.

The desired properties of the latch cones were possible to achieve with respect to both material properties and dimensions. In table 5 below compressive strength of the warm compacted cones are compared to the precision forged and the powder forged ones after induction hardening. 10 teeth of each latch cone were tested for the three different processing conditions.

		Precision forged	Powder forged	Warm compacted
Density teeth, g/cm^3		7,89	7,47	7,32
Density ring, g/cm^3		7,81	7,60	7,17
Failure force, KN	Mean value	4,75	1,68	2,91
	Standard dev.	0,25	0,63	0,16
Failure work, NM	Mean value	4,25	0,38	1,02
	Standard dev.	0,41	0,32	0,12

Table 5. Comparison of compressive strength of latch cones obtained by different processing conditions

From the table it can be seen the precision forged cones have the highest failure force, failure work and failure deformation followed by the warm compacted cones. The lowest values were obtained for the powder forged cones.

As warm compaction is estimated to be considerably more cost effective than both precision forging and powder forging the results of this study show the great potential for PM to make its inroad into new highly stressed applications.

CONCLUSIONS

Warm compaction has become an established production method which offers possibilities to cost effectively obtain improved static and dynamic properties that before were possible to obtain only by double pressing and sintering.

By applying warm compaction to partially pre-alloyed powders(Distaloy), fully prealloyed powders (Astaloy CrM) and powders based on combinations of these alloying methods (Distaloy HP-1) tensile strength levels ranging from 800-1100 MPa. can be obtained already after compaction and sintering.

Axial fatigue strength levels in the range 275-300 MPa can be achieved with Distaloy HP-1 after warm compaction, sintering and tempering which shows that PM materials can compete with conventional forged or powder forged materials for high strength applications.

By utilising warm compaction of low alloyed steel powders new high performance applications such as synchronising parts, connecting rods and different kinds of highly stressed gears can become feasible both from technical and economical point which will contribute to an extended use of PM in the future.

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