MATERIAL FOR WARM COMPACTED HEAVY TRUCK TRANSMISSION PART

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1. ABSTRACT

P/M steel synchronizing parts for automotive transmissions are commonly used in passenger cars today, but larger and more stressed parts such as those used in transmissions for heavy trucks can also be realized.
A synchronizing latch cone aimed for the gear switch in a 500 bhp heavy truck is a highly stressed component. In a feasibility study prototype latch cones of Fe-Cu-Ni-Mo material were warm compacted to high density. The prototypes were evaluated with respect to material properties and dimensions.
The warm compacted latch cone met all the requirements, including a gear box test and is therefore an interesting alternative offering cost savings compared to existing methods.

2. INTRODUCTION

Billions of parts are annually produced with consistent properties and dimensions by the well-established uni-axial compaction process. To use warm compaction only minor modification of the uni-axial compaction process is required. A powder heater and a provision to heat the compaction tool are added. Standard lubricants are not capable of operating at the temperatures used (130-150^{o}C; 270-300^{o}F) and a powder with improved lubricant is used (Densmix™). This modest upgrade requirement gives the potential for existing manufacturing facilities to produce components with greatly improved material properties. The major benefits are increased density, fatigue limit and green strength. The increase in green strength opens for machining of warm compacted P/M parts prior to sintering with unsignificant tool wear and very low cutting forces.

3. LATCH CONE FOR TRUCK GEAR BOX

Manual gear boxes for passenger cars are often supplied with pressed and sintered synchronizing-rings and synchronizing-hubs. Thanks to new processes leading to higher densities in combination with tailor made micro structures, it is possible to realize more demanded parts such as the latch cone for trucks. The latch cone is a part of the synchronizing system in the Scania gearboxes for heavy trucks. In each gearbox there are three or four latch cones of this type, depending on the number of gears. An overview and a close up of the mechanism of the gearbox are presented in figure 1.

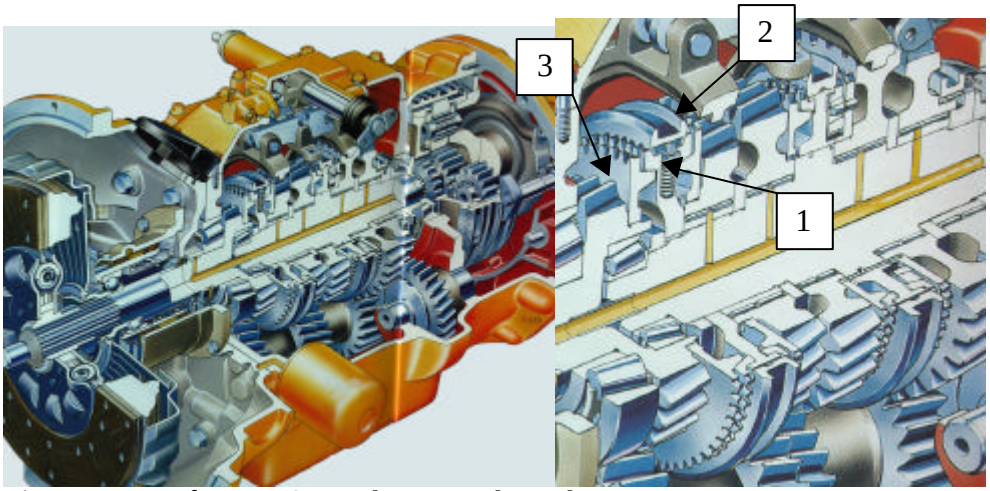


Figure 1. Left:: Scania heavy truck gearbox - overview
Right: Gear and synchronization mechanism – close up
1-latch cone # 2-synchronizing ring # 3-gear cone

The latch cone is only active during the changing of the gear. The synchronizing ring pushes the latch cone towards the gear cone. Once the speed of the ring and the gear cone is the same, the ring will slip over the teeth of the latch cone and engage the teeth of the gear cone. Once this has happened, the function of the latch cone is over.

Table 1. Gear box details

Type:	Manual – 14 speed
Max.torque:	2,300 Nm (1,696 foot-lbs)
Max. engine power:	500 bhp

Current latch cones are manufactured via two routes; precision forging or powder forging. See figure 2 and table 2.

Precision forged cones are made from SS1672 steel with a carbon content in the range 0.42-0.50%. A carburization treatment is carried out after forging in order to compensate for decarburization during the forging.

Table 2. Typical composition (wt.%) of material used in precision forged and powder forged latch cones

	Ni	**Mo**	**C**	**Si**	**Mn**	**P**	**S**	**Fe**
Precision forged	-	-	0.42-0.50	0.15-0.35	0.5-0.80	<0.035	<0.035	Bal.
Powder forged	1.80-2.20	0.50-0.60	0.10-0.25	-	0.20-0.30	-	-	Bal.

After forging, the tapered surface is machined and the rear side of the ring is ground. The machining is carried out in order to remove burr and to create the conical surface with the desired accuracy. The teeth are induction hardened while rotating. The entire tooth should be through hardened. A minimum of 55 HRC is required on the outer perimeter of the tooth flank.

The microstructure of the tooth consists of undissolved ferrite and martensite. The ferrite can be accepted as long as the hardness is reached. In the tooth fillet and the rest of the cone, the material is unaffected by the hardening.
The tapered surface of the ring is shot peened and a thin (0.3 mm) layer of molybdenum is plasma sprayed onto it. The layer is machined in order to achieve good tolerances and to give the surface a prescribed texture.
Powder forging is used as an alternative to precision forging. It is forged almost to final shape. The tapered section is machined in order to achieve the desired tolerances for the diameter and cone angle. Deburring of the side surfaces is performed. The composition of the material in the powder forged cone is presented in table 2. In order to reach sufficient hardness, case hardening is performed. The hardness must reach 200 HB and the density should be above 7.6 g/cm^3.
This material composition and process lead to a microstructure that consists of ferrite and pearlite.
In a similar procedure as for the precision forged cone turning, molybdenum coating and ID grinding are performed on the powder forged components. In order to avoid the risk of fretting fatigue of the tooth flank a minimum hardness is specified for this area tooth.

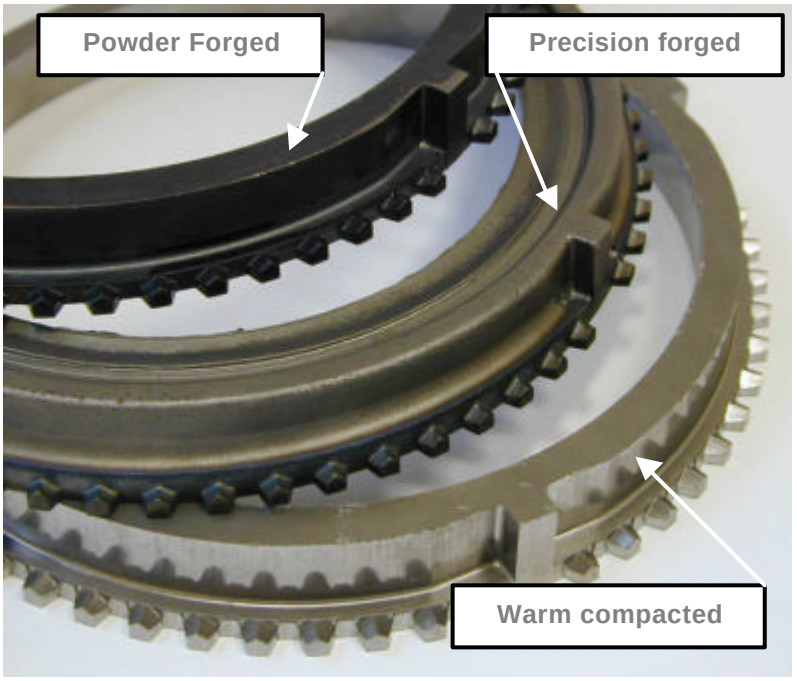


Figure 2. Sections of latch cones: powder forged, precision forged and warm compacted

4. DESIGN OF WARM COMPACTED LATCH CONE

The objective of the design was a latch cone with maximum wear resistance of the teeth and sufficient strength and dimensional stability of the ring section. The part should fit the existing gear box and therefore the possible design modifications were limited. When the process route was outlined, the ambition was to consider all steps in the process with the emphasis on eliminating costly processing steps. A minor re-design was carried out in order to make optimum use of the shaping ability of the P/M process and minimize the compaction tool complexity. See figures 3 and 4.

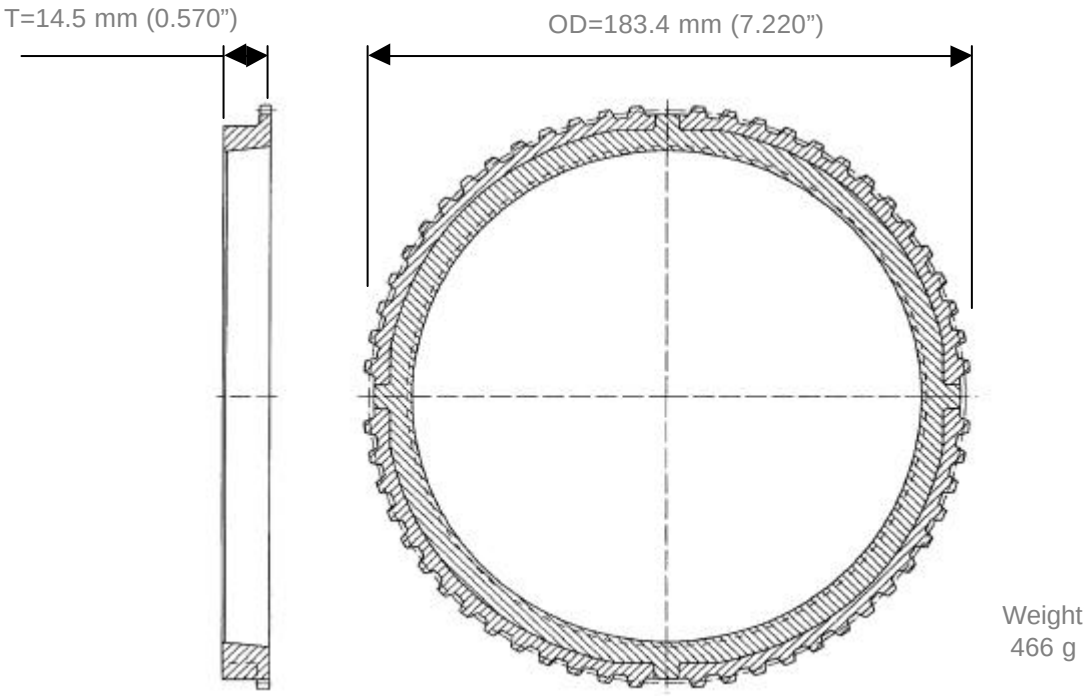


Figure 3. Warm compacted latch cone for Scania heavy truck gear box

Adaptation of warm compaction capability of the tool did not add any design limitations for the component. By having two lower punches, the part can be supported during the critical stage of ejection. This means that crack free parts can be made despite the relatively large springback of such a big component. The drawback, in particular for full-scale production, with this design is that burring can occur on the tooth flank.

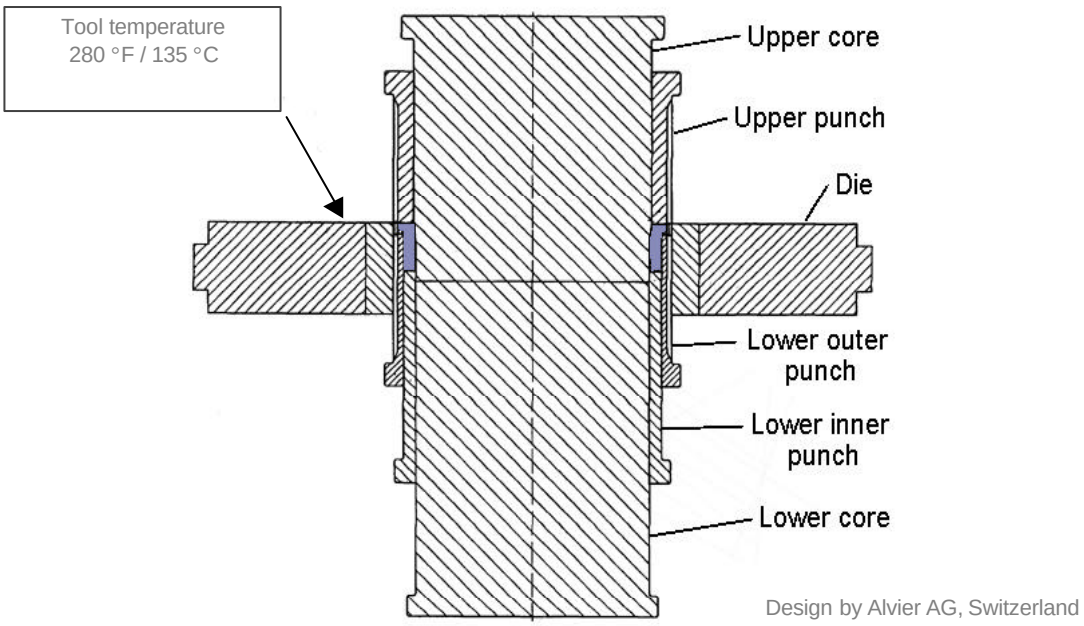


Figure 4. Warm Compaction tool for latch cone

Since the teeth need to be wear resistant the tool was designed in order to make it possible to maximize the density locally in the teeth region. The desired density was 7.3 g/cm^3 in the teeth and 7.1 – 7.2 g/cm^3 in the ring section.

5. MATERIALS SELECTION

The most important material requirement for the latch cone is the hardness of 55 HRC in the teeth. Also the warm compacted cones are induction hardened using a similar procedure as for precision forging and powder forging. A natural material selection is therefore a diffusion alloyed grade (D.AB) with graphite addition, since this material achieves high strength and responds well to the induction heat treatment. This type of materials consist of very pure iron powder to which finely divided alloying elements have been diffusion bonded. In this way, the high compressibility of the iron powder is maintained, the fine alloying additives are well utilized and the risk of segregation is minimized. To reach the hardness of 55 HRC, D.AB with a graphite addition of 0.5 % is selected. A hardness of 55 HRC equals approximately to 550 HV_5.
D.AB is partially prealloyed with 0.5 % molybdenum, 1.75 % nickel and 1.5 % copper. The chemical composition makes the material very suitable for heat treatment and thanks to the relatively low nickel content, the austenite (soft phase) content after hardening is low.
The properties after warm compaction at 700 MPa, sintering 30 minutes at 1120° C in endogas are presented in table 3.

Table 3. Properties of Warm Compacted material made of press ready mixed powder type D.AB + 0.5%C Densmix ™

Sintered density (g/cm³)	7.33
Ultimate Tensile Strength (MPa)	709 (102,800 psi)
Yield strength (MPa)	410 (59,500 psi)
Elongation (%)	3.4
Hardness after sintering (HV10)	210
Dimensional change (tool to sintered part):	+ 0.18 %

Compaction pressure 700 MPa (50 tsi), Sintering 1120 °C (2050°F), for 30 min in Endothermic atmosphere, cooling rate 1°C/sec (2°F/sec.)

The microstructure of the material after sintering is a mix of different phases. With a cooling rate of 1° C/s, the selected material has approximate phase amounts according to table 4.

Table 4. Typical phase constituents of Warm Compacted material made from press ready mixed powder type D.AB + 0.5%C Densmix ™

Structural component	Approximate Area fraction
Martensite	30 %
Bainite	Totally 43 %
Pearlite	
Austenite	2 %
Ferrite	25 %

Compaction pressure 700 MPa (50 tsi), Sintering 1120 °C (2050°F), for 30 min in Endothermic atmosphere, cooling rate 1°C/sec (2°F/sec.)

Regarding micro graphs see figures 6 - 8.

Warm compaction improves the compressibility of the powder. In order to take fully advantage of this, the organic content must be minimized in order to reach high density. Lubricants must therefore be efficient also at low additions. The warm compaction powder, Densmix™, has proven to result in low friction and stable physical properties. The amount of lubricant in the mix used for the latch cones was 0.6%.

6. PROTOTYPE MFG

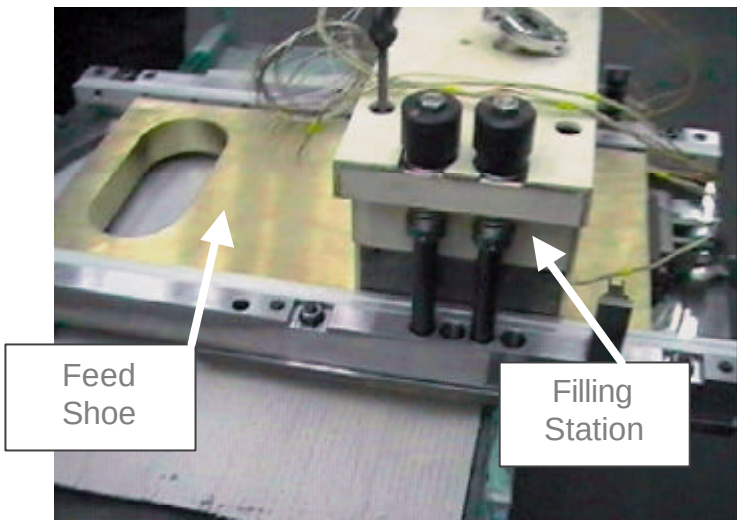
A straight forward and cost efficient process with a minimum of manufacturing steps was used for the manufacturing of the prototype latch cones, which were finished, tested and evaluated by the Swedish Heavy Truck manufacturer Scania. The process described below is based on single pressing and sintering. Prototypes were manufactured using a standard mechanical Dorst TPA press upgraded for warm compaction. Densmix™ based on a diffusion alloyed iron powder, D.AB (Fe, 1.75Ni, 1.5%Cu, 0.5%Mo) + 0.5%C was used. Processing data is given in table 5.

Table 5. Processing data for warm compacted prototype latch cones

Warm compaction	**Powder**	**Press Ready mix type D.AB+0.5% Densmix ™**
Powder Compaction	**Compaction press:**	**450 ton multiplaten mechanical Dorst TPA press**
	Compaction Pressure:	640^{o} MPa (46 tsi)
	Pressing Force	405 tons
	Tool:	Steel die - 1 upper + 2 lower punches, 2 cores
	Powder-/tool temp.:	125^{o} C / 135^{o} C (260^{o} F / 280^{o} F)
	Pressing speed:	4 strokes/min
Sintering	**Sintering furnace:**	**Continuous mesh belt furnace**
	Sintering:	1120^{o} C (2050^{o} F) for 20 min. Endothermic atmosphere Cooling rate 1^{o} C/sec (2^{o} F/sec)
Turning of ID		
Induction hardening	Induction Hardening of Teeth	
Mo-coating	Plasma Spraying Process	
ID grinding		

The tool has two lower punches, one upper punch and two core rods. The lower core rod is used during the filling and the pre-compaction stage. The upper core rod is conical and forms the tapered section in the centre of the ring. The main tool members are illustrated in figure 4 . The press was equipped with a powder heater that heats the powder before it enters the filling system of the press. The hose for powder supply and the filling shoe are also heated.

Figure 5. Powder fill system



All three manufacturing methods, warm compaction, precision forging and powder forging, were compared with respect to complexity and performance to mass-produce parts. The weight of the blank for the precision forged cone is 1220 gram, while the weight of the finished part is 446 gram.
In the case of warm compaction, a minimum of manufacturing steps and manufacturing equipment are needed due to the surface finish and dimensional tolerances on pressed and sintered parts. A consequence of this is high material utilization and a minimum of machining. For warm compaction, the number of operations is reduced compared to the two other manufacturing alternatives.

7. ANALYSIS OF PROTOTYPES

7.1. Dimensions

In order to study the consistency and the general outcome of the manufacturing campaign the prototypes were tested with respect to material properties, mechanical performance and dimensions. See table 6. All the components passed a test jig (go - no go gauge) that secures the dimensional functionality of the latch cone.

Table 6. Properties of warm compacted latch cones after the stage of sintering

	Drawing requirements		**Outcome**	
Measure	**Nominal**	**Range**	**Average**	**Range**
OD (mm)	183.4 (7.2205”)	0.4 (0.0157”)	183.46 (7.2228”)	0.48 1) (0.0189”) (Out of Roundness)
Height (mm)	14.5 (0.5707”)	0.27 (0.0276”)	14.56 (0.5732”)	0.18 (0.0071”)
Weight (g)			466	4

Dimensions are based on readings from 20 components - weight is based on 40 components

1) comment: the range for the mean diameter is 0.1 mm (0.0039”)

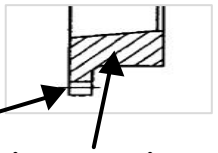
It was possible to reach the desired component properties. Density and dimensions after the stage of sintering are important. The roundness of the parts can be improved by a more gentle pick and place device that does not deform the components when picked up after the stage of compaction. See table 6.

7.2. Density

Density measurements were performed in the teeth region and in the ring section. Five teeth were cut out and one piece of the ring section. Precision forged, powder forged and warm compacted synchronizing latch cones have been compared.

The precision forged synchronizing latch cone is free from porosity and thus has the highest density. The powder forged component has a higher porosity and thus a lower density. This can be explained by the fact that the powder forged latch cones have not been compacted sufficiently at the forging, especially in the thin walled teeth region. Warm compacted and sintered latch cones have a somewhat lower density than the powder forged ones.
They also have a higher density in the teeth region than in the ring section. See table 9 and figure 5. By control of the press cycle, the densification is maximized in the most demanded areas of the component.

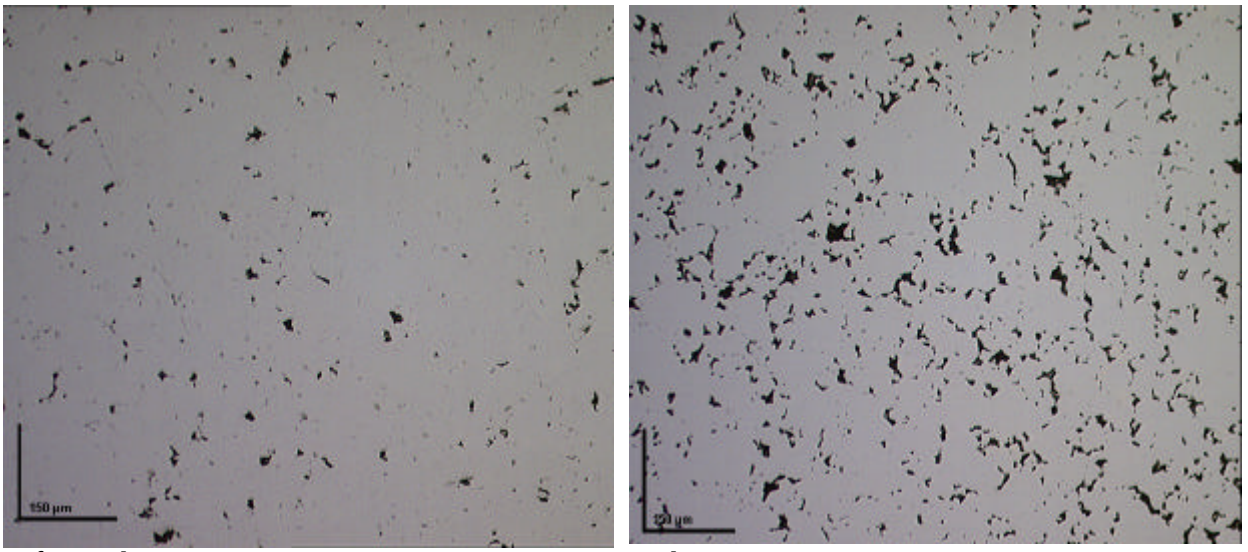
Table 7. Densities of synchronizing latch cones (g/cm^3)



	Teeth	Ring section
Precision forged	**7.89**	**7.81**
Powder forged	**7.47**	**7.60**
Warm compacted	**7.33**	**7.16**

7.3. Microstructures

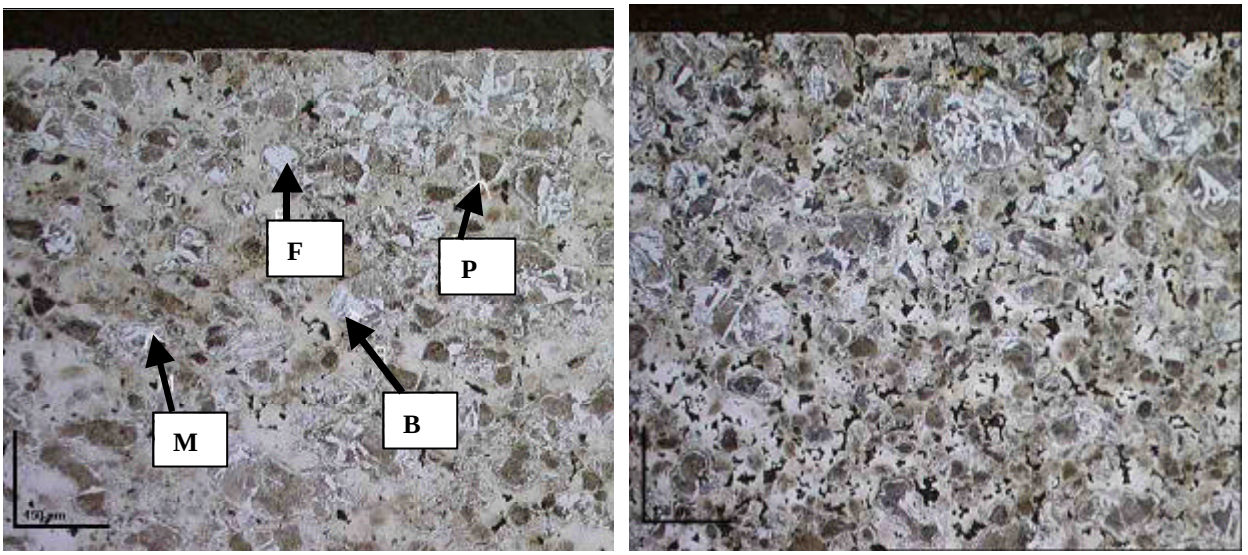
The metallographic examination agrees with the density measurements and confirms that the porosity is significantly lower in the tooth region than in the ring section. This can be clearly seen from figure 6 showing the pore structure.



Left: Tooth region Right: Ring section

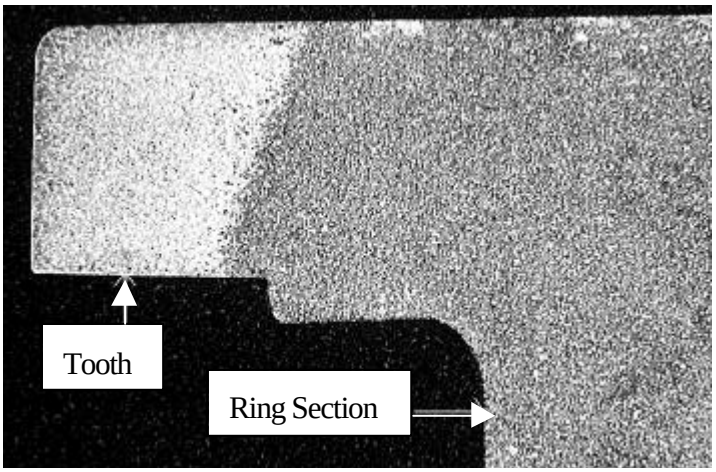
Figure 6. Micro structure of Warm Compacted syncronizing latch cone - unetched

In the micrographs of sintered latch cones presented in figure 7 the phase constituents were identified to Martensite, Ferrite, Bainite and Pearlite.



Left: Tooth region Right: Ring section
F=Ferrite B=Bainite M=Martensite P=Pearlite
Figure 7. Microstructure of Warm Compacted syncronizing latch cone – as sintered, etched

Induction hardening of the teeth region has been performed. See figure 8. The size of the induction hardened area depends on the heating time. In comparison to precision forged synchronizing latch cones, the heating time to achieve hardening of the teeth was shorter for the warm compacted components.



Heating time 3.3 sec.
Figure 8. Induction hardened tooth of warm compacted latch cone

7.4. Hardness

The hardness was measured in the teeth region after sintering and after induction hardening. Table 8 shows the mean values after five indentations of each specimen.

Table 8. Teeth Hardness of syncronizing latch cones

Specimen	Hardness HV0.5 0.1 mm from the surface	Hardness HV0.5 0.5 mm from the surface	Hardness HV5 centre of tooth
Precision forged hardened	601	628	669
Powder forged hardened	605	687	692
Warm compacted hardened	647	643	524
Warm compacted before hardening	198	215	201

All the observed values indicate that the specification of 55 HRC can be met.

8. COMPONENT TESTING

Prototypes were tested in order to verify compressive strength, impact strength at both room temperature and at low temperature. Finally a gear box test was performed in order to verify the functionality of the component.

Compressive strength testing

The compressive strength of the teeth was measured in a tensile testing machine. See figure 9. Ten teeth of each component were tested. The results are summarized in table 9.



Figure 9. Compression test of latch cone teeth.

Precision forged synchronizing latch cones have the highest failure force, the highest failure work, and the highest failure deformation. The mechanical performance of the powder forged and the warm compacted latch cones is very similar and they both meet the requirements of the end user. See table 9.

Warm compacted latch cones in the state as sintered respectively as induction hardened, was also tested but no difference in compressive strength could be observed.

Table 9. Compressive strength of latch cone teeth at room temperature (+23° C)

Mean value	Failure force (kN)	Failure work (Nm)	Failure deformation (mm)
Precision forged	4.75 (1,067 lbs)	4.25 (3.134 lbs-ft)	1.71 (0.0673")
Powder forged	1.66 (323 lbs)	0.38 (0.280 lbs-ft)	0.60 (0.0236")
Warm compacted	2.91 (654 lbs)	1.02 (0.752 lbs-ft)	0.73 (0.0287")

Test temperature +23°C (73.4°F)

Impact strength testing

The impact strength of the latch cones were measured in an impact tester, see figure 10, at both room temperature and at low temperature, -40° C (-40° F).
Ten teeth of each component were tested. The results are summarized in table 10.

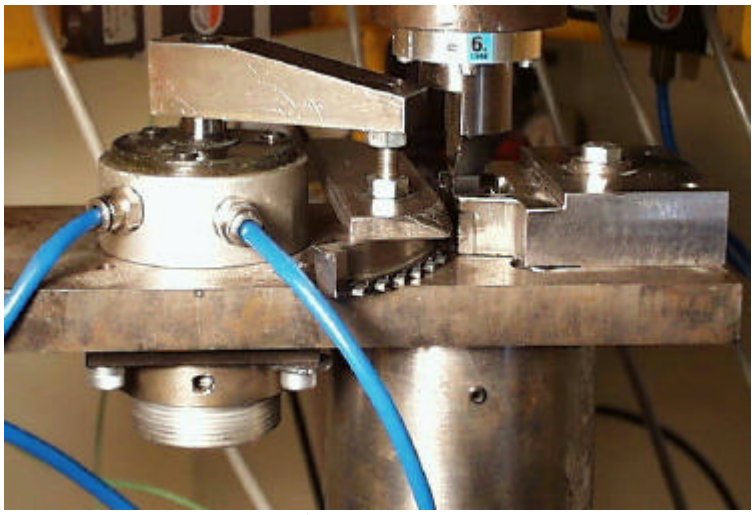


Figure 10. Impact test of latch cone teeth

The precision forged synchronizing latch cone has the highest fracture energy. The warm compacted synchronizing latch cone has lower values. The powder forged synchronizing latch cone has values near those of warm compacted components.

Table 10. Impact test of latch cone teeth peak values at room temperature (+23° C ; 73.4° F)

Mean value	Failure energy (J)	Fracture force (N)	Fracture deformation (mm)
Precision forged	2.22 (163 lbs-ft)	7525 (1,691 lbs)	0.65 (0.0256")
Powder forged	0.48 (35 lbs-ft)	4235 (952 lbs)	0.59 (0.0232")
Warm compacted	0.55 (40 lbs-ft)	4441 (998 lbs)	0.43 (0.0169")

Mass: 10.3 kg Velocity 3.00 m/sec. Impact height 0.459 m Energy 46.36 J

The results from the testing conducted at low temperature (-40° C, 73.4° F) were essentially the same as for the tests performed at room temperature.

Gear box testing
The purpose of the test was to determine if the warm compacted latch cone meets the requirements during service in a gear box. The test was carried out in a Scania synchronizing test bench. A standard test cycle was used where the test is performed on a complete gear box and gear changing between two gears in a specific pattern is selected.

In the first test the warm compacted latch cone passed 2 million cycles. The tested components were inspected after the finished test. No remarkable wear, damage or other observations were made. An endurance test in a truck has pointed out that the wedge shaped region between the teeth can be a potential spot for crack initiation. This can easily be eliminated by modifying the tool design.
In another test made in a truck, wear of the head of the warm compacted latch cones was observed. As a result of this the head section will also be induction hardened in order to eliminate wear.

The tests have shown the capability of the warm compacted latch cones and indicated areas were minor design improvements will increase the mechanical performance of the component.

9. CONCLUSIONS

A syncronizer latch cone for a heavy truck has been produced by warm compaction.

Warm compacted, precision forged and powder forged latch cones have been subjected to compressive tests and impact tests.

The warm compacted syncronizer latch cone has been endurance tested in a truck and met the requirements.

The cone will be introduced as a component in the gearbox with minor changes in the design.

The changeover to warm compacted synchronizer latch cones gives a considerable lower cost compared to the current precision forged or powder forged parts.

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