FUNCTIONAL MATERIAL DESIGN FOR HIGH-DENSITY PM CONNECTING RODS

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1. ABSTRACT

A con rod for a modern passenger car engine has been studied to show the performance of high-density PM-materials manufactured by warm compaction of high compressible low alloyed powders.
The con rod design was optimized with respect to weight and fatigue performance by finite element analysis. Prototypes manufactured from the diffusion alloyed powder D.HP1 with 0.7%C have been tested and found to meet the design goal of a fatigue safety factor exceeding 1.5 at engine peak power. Results from the endurance tests on these warm-compacted con rods were used as a base for further improvements of mechanical strength and reliability of the manufacturing process.
Fractographic investigations have led to both a better understanding of the probability for failure, as well as suggestions to design improvements for reduced scatter of fatigue strength.

This paper presents a functional material design for warm compacted connecting rods with a performance similar to the currently used con rods. The design and the procedure for prototype manufacturing are described. Results from fatigue tests on both test samples and connecting rods are given. The results show that warm-compaction of robust low-alloyed powders offers the potential of reduced total cost due to less machining and fewer processing steps.

2. INTRODUCTION

Automotive parts are mass-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. Lubricants used in standard powder mixes are not capable of operating at the temperatures used (130-150^{o} C; 270-300^{o} F) and a powder with improved lubricant (Densmix™) is therefore used in the case of warm compaction. 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 insignificant tool wear and very low cutting forces.

3. CONNECTING RODS FOR A GASOLINE ENGINE

Gasoline engines for passenger cars are mostly supplied with connecting rods that are cast, powder forged or forged. For engines produced in large numbers, powder forged rods are widely used because they are both reliable and cost efficient. Thanks to the development of new processes, such as warm compaction, pressed and sintered connecting rods can be made to a fatigue performance that match the presently used powder forged standard rods but with less manufacturing steps and improved materials utilization. There is a potential for significant cost savings.

This study is a continuation of a development (ref. 3) which purpose is to show the feasibility of and to get acceptance for warm compacted connecting rods, both technically and economically. Warm compacted prototype rods have earlier been made (ref. 1) for a four-cylinder engine and they were found to meet a safety factor requirement of 1.5 at peak power condition.

Table 1. Engine Data

Configuration:	In line - 4 cylinders
Type:	Gasoline 2.2 l
Power:	100 kW @ 5600 rpm
Max Firing Pressure:	73 bar
Bore x Stroke:	86.0 x 94.6 mm
Cylinder centers:	96.0 mm
Connecting rod centers:	146.5 mm
Crank pin diameter:	49.0 mm

This particular four-cylinder engine (See table 1.) is in its standard version supplied with either powder forged or conventionally steel-forged connecting rods and is therefore suitable for comparisons.
The standard rods, shown in Fig. 1 below, were tested in order to determine their endurance limit.

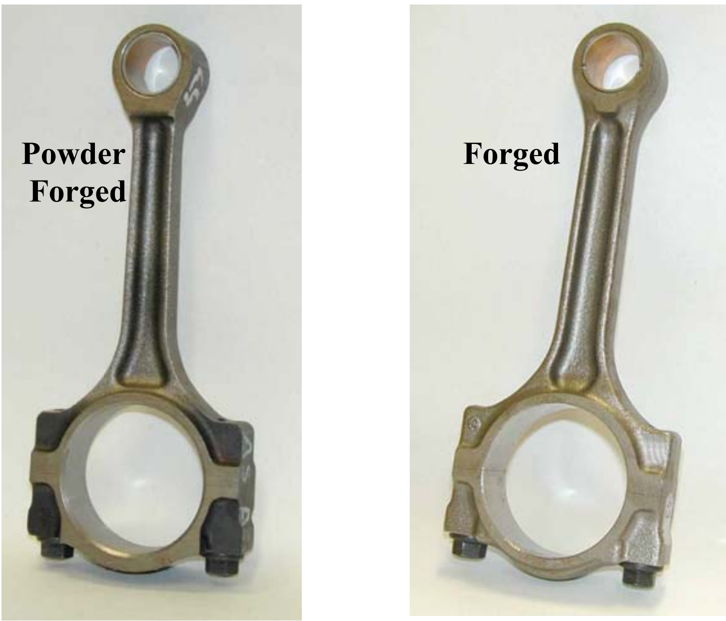


Figure 1. Standard connecting rods: Powder forged and conventionally steel forged

A connecting rod is subjected to a cyclic load during its service. Forces due to the cylinder pressure as well as the mass of the connecting rod and the piston assembly are illustrated in Figure 2.

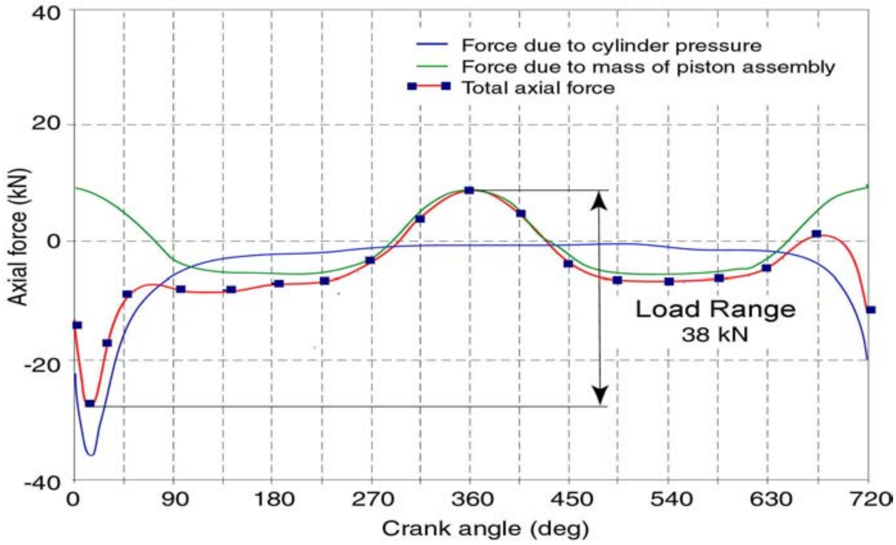


Figure 2. Connecting rod forces at engine peak power

The load pattern illustrated in the figure above and the design criteria for the connecting rod lead to the test method used in this study. The compression force is approximately twice the tensile force at engine peak power and the load range at the same engine condition is 38 kN.
If a minimum safety factor of 1.5 is required, a successful series of tested components must survive a run out load range of at least 57kN.

4. WARM COMPACTED CONNECTING RODS

When the process route for the warm compacted connecting rods was outlined, the ambition was to consider all steps in the process with the emphasis on eliminating costly processing steps.
The result is a straightforward and efficient process (See Table 2.), which fully utilizes the shaping ability of warm compaction and the advantages of machining prior to sintering as well as fracture splitting of the big end. Prototypes were manufactured, according to the route described in Table 2., in order to prove the functionality of the process and obtain test objects for verification of the fatigue performance of actual full-scale components.

Table 2. Processing route for prototype connecting rod

Powder: Densmix	**D.HP1 + 0.7% C-UF**
Warm Compaction	**Compaction press: 400 ton hydraulic press** *Compaction Pressure: 800 MPa (58 tsi)* *Tool: Steel die - 3 upper + 3 lower punches, 4 cores*
Drilling and Tapping	*Powder-/tool temp.: 125° C / 135° C (260° F / 280° F)* *Pressing speed: 4 strokes/min*
Sintering	**Sintering furnace: Continuous mesh belt furnace** *1120 °C (2050 °F) 30 min 90%N_2 + 10%H_2*
Fracture Split	
Tempering	*200 °C (400 °F) air*

The three manufacturing methods; warm compaction, powder forging and conventional forging are compared with respect to complexity and performance to mass-produce parts. 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. The consequence of this is high material utilization, a minimum of machining and a reduced need for investment in production equipment. For warm compaction, the number of operations is reduced significantly compared to other manufacturing alternatives.
A comparison of the warm compaction route and the two other established manufacturing methods used for the standard connecting rods is presented in Figure 3.

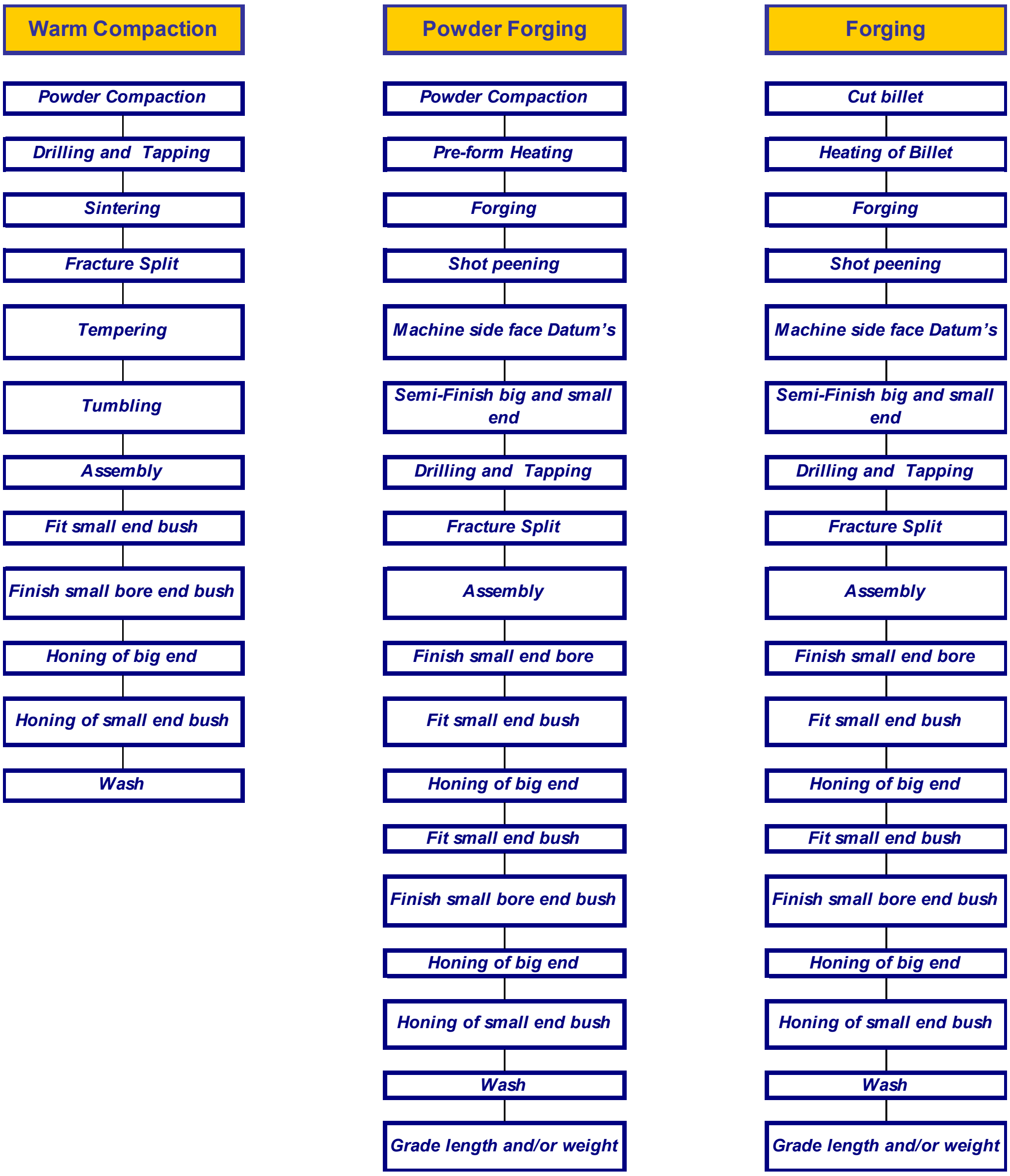
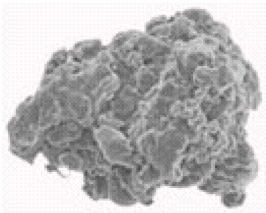


Figure 3. Processing route for connecting rods

5. MATERIALS

The axial fatigue properties and the yield strength are of utmost importance for a connecting rod and therefore the warm compacted prototypes are made of a high strength Fe-Ni-Cu-Mo-C material. The powder used is a press ready mix type Densmix™ based on a diffusion alloyed grade D.HP-1 + 0.7%C. D.HP-1 (HP= High Performance) is a low-alloyed powder which, when admixed with graphite, pressed and sintered, reaches a very high strength with a dimensional change that is close to zero. The powder which is alloyed with 4% nickel, 2% copper and 1.5% molybdenum, is manufactured by diffusion-annealing Astaloy Mo with nickel and copper. Astaloy Mo is a prealloyed, water-atomized powder with 1.5% molybdenum.



D.HP1

Fe + 4Ni + 2Cu +1.5Mo

Figure 4. Diffusion alloyed powder type D.HP1

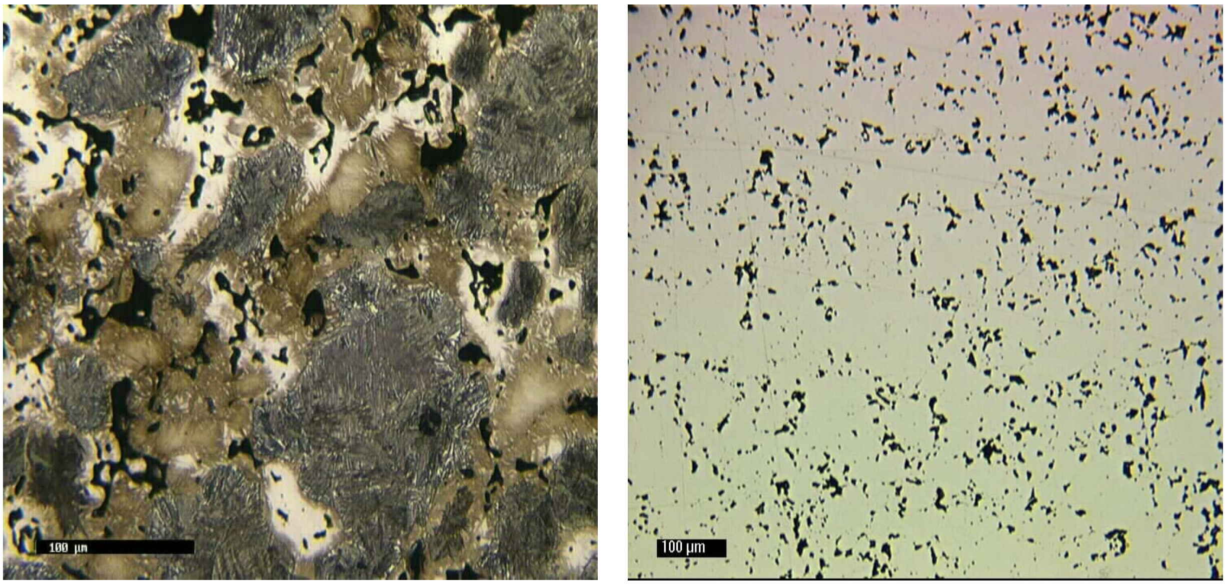
The annealing technique prevents segregation of the mix and gives a powder with a stable dimensional change. This allows close tolerance parts to be manufactured under normal sintering conditions in belt furnaces with tensile strength of 950-1000 MPa. Properties of this material after sintering 30 minutes at 1120 ^oC (2050 ^oF) in N_2-based atmosphere are listed in Table 3. After sintering and fracture split, tempering is performed in order to increase the ductility. It is favourable to fracture split before tempering since the splitting force becomes smaller and the distortion of the big end negligible.

Table 3. Materials data from pressed and sintered test specimens used for Finite Element Analysis

	Warm compacted D.HP-1 + 0.7%C	
Density	7.35 g/cm^3	
Poissons ratio	0.26	
Young's modulus	165 GPa	24000 ksi
UTS	940 MPa	136 ksi
Yield strength	540 MPa	78 ksi
Compressive strength 1)	621 MPa 1)	90 ksi
Axial fatigue limit (R = -1)	260 MPa	38 ksi
Bending fatigue limit	300 MPa	43,5 ksi

1) calculated

The structure after sintering consists of 2/3 Martensite, 1/3 Bainite and a few percent of Austenite (Figure 5).



as etched **as polished**

Material: Diffusion alloyed grade D.HP 1 (Fe, 4% Ni, 2% Cu, 1.5% Mo) + 0,7% C
Sintered at 1120 °C (2050 °F) for 30 min in 90%N_2+10%H_2 atmosphere

Figure 5. Metallographic structure of Warm Compacted an sintered connecting rod material

6. DESIGN OF WARM COMPACTED CONNECTING RODS

The first version of warm compacted prototypes (ref 3) was designed to survive a 50 % higher load than the cyclic fatigue load range at engine peak power condition and still be lighter than the standard P/F rods. Other important design criteria were to fit the existing engine and to allow manufacturing with a simple and uncomplicated process.

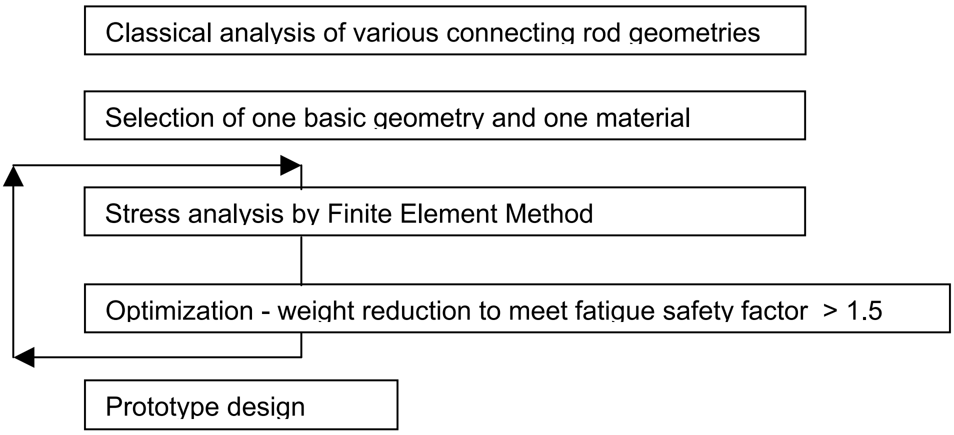


Figure 6. Design route for prototype connecting rod (first version)

Prototype rods of the first version have been manufactured and tested. The test results confirmed that a safety factor of minimum 1.5 was achieved. Also the weight of the finished rod was lower than for the standard P/F rods.
After evaluation of the fatigue test results and the fracture analysis of the first version of prototypes, various design modifications were suggested in order to improve the fatigue performance and the robustness.
In order to prove the functionality and achieve acceptance of warm compacted rods, a second version of prototypes was designed. Instead of proving a specific minimum fatigue safety factor, the approach for the second version was to match the performance of a currently used standard connecting rod. Therefore both P/F and steel forged connecting rods were fatigue tested in order to determine their survivable fatigue load.

Table 4. Design criteria for Warm Compacted con rod (version II)

* Fit existing engine
* Match performance of P/F rod
* Minimized weight
* Uncomplicated manufacturing process

Encouraging results from the first test round of warm compacted rods convinced the designers that considerable strength improvements were possible just by modification of the shank region and that this in turn required a redesign of the middle punches and the two middle core rods. A larger cross section area, CSA, was obtained by increasing the width of the legs. This leads to a more favourable width/height ratio, which in turn improves the compaction and results in less density drop in the neutral zone. Also, the radius of the shank inner section was increased in order to reduce stress concentrations.
See figure 7 and figure 8.

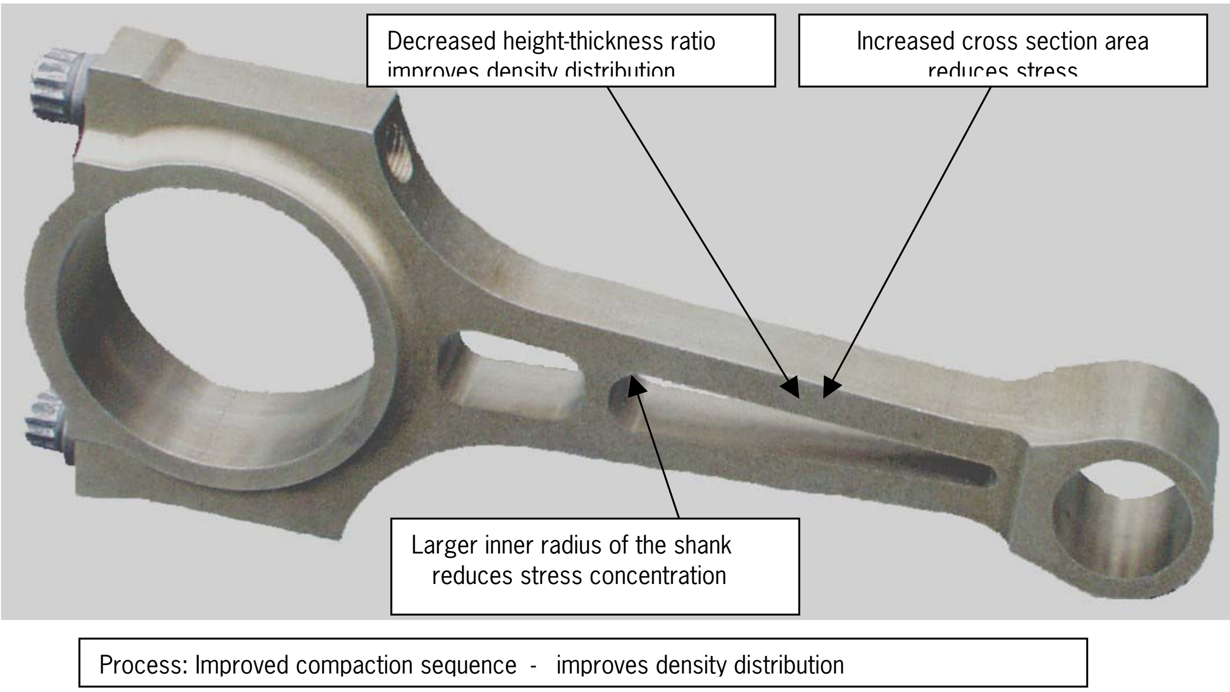


Figure 7. Design- and process improvements of prototype con rod –II

Better synchronization of tool movements can also lead to reduced density variation and improved robustness of the manufacturing method.

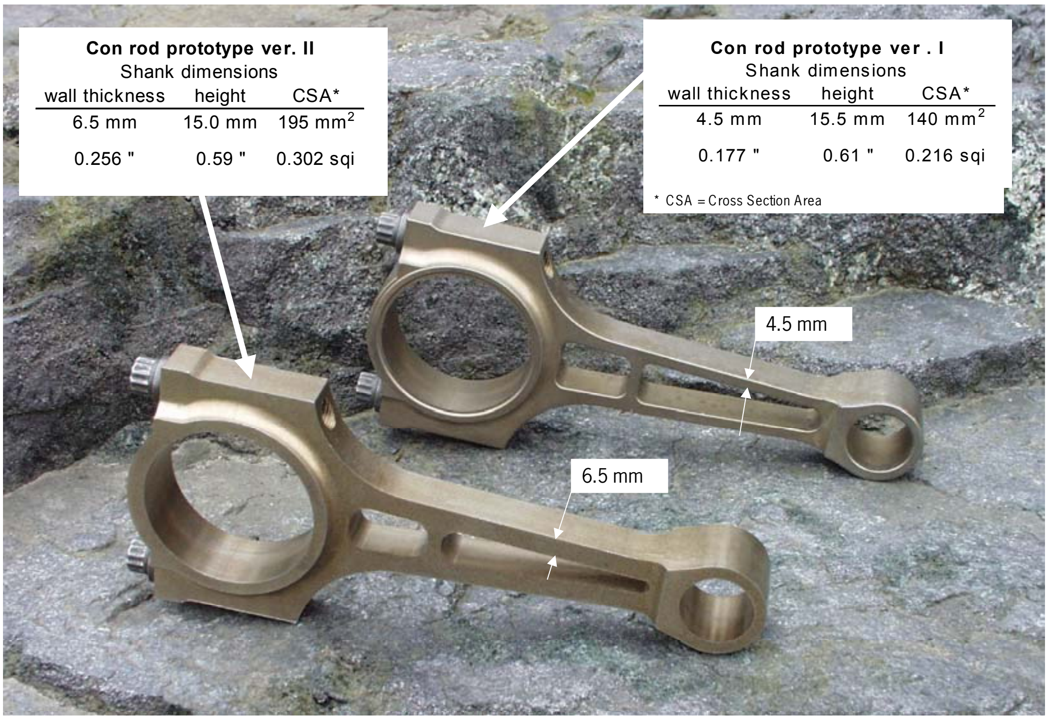


Figure 8. Re-design of Warm Compacted prototype connecting rod

All four versions of connecting rods, the first and the second generation of warm compacted rods together with the powder forged and the steel forged rods were compared with respect to use of raw materials, weight of final component and materials utilization. See table 5.
The weight of the second version of warm compacted rods is equal to the weight of a steel forged standard rod. However, the same warm compacted rod requires less amount of raw material than both the powder forged and forged alternatives. Because of this, the warm compacted rods show the most attractive materials utilization.

Table 5. Comparison of connecting rods

	Warm Compaction		Powder	Steel
	ver. I	**ver. II**	Forging	Forging
Raw material weight	515 g	**550 g**	560 g	850 g
Weight of finished rod 1)	475 g	**510 g**	485 g	510 g
Materials utilization	0,92	**0,92**	0,87	0,60

1) Excluding bolts and bushings

7. PERFORMANCE OF CONNECTING RODS

The performance of the connecting rods, expressed as the survivable fatigue load range, was determined by a push pull-test that was set up to be representative for this particular engine and the design criteria. For a gasoline engine running at peak power, the compression force is twice the tensile force and therefore a load case of R= - 2 was used.
Finished rods including, bearings, bolts, bearings and bushings were tested in the hydraulic rig shown in figure 9. The test duration is 10 million cycles and the frequency 25 Hz. Oil was introduced at the bearing surfaces in order to lubricate and to avoid fretting.

Push-pull test

Load case:	R=-2
Duration:	10^7 cycles
Outcome:	SFL (kN)*

Tested con rods

Steel Forged
Powder Forged
Warm Compacted, first version

* SFL = Survivable Fatigue Load

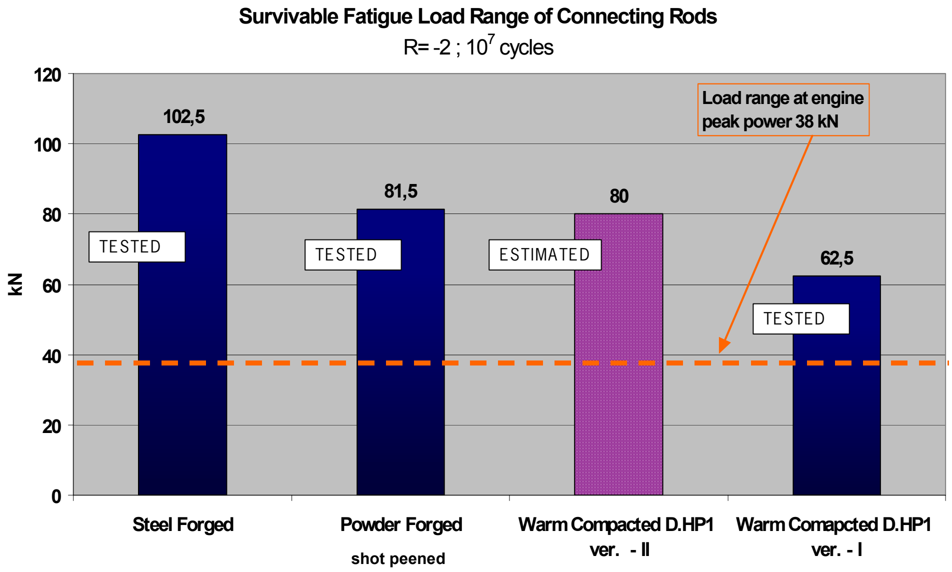
Figure 9. Fatigue testing of connecting rods

The survivable fatigue load range for the first version of warm compacted prototype rods made of D.HP1+ 0.7%C is 62.5 kN. This is 63 % more than the load amplitude at engine peak power and proves that design criteria of a minimum safety factor larger than 1.5 was met.

Conventional steel forged rods were found to survive the highest fatigue load, 101 kN.
Powder forged standard rods, shot peened in order to build in compressive stresses in the surface, survived a load range of 81.5 kN.
Shot peening improves the bending fatigue properties significantly, while its influence on axial fatigue is smaller. Shot peening of warm compacted rods of the design presented in this paper is most likely not feasible because of the difficulty to reach and penetrate the inside of the shank region sufficiently.

The second version of warm compacted prototype rods are expected to survive a fatigue load range of at least 80 kN, mainly due to increased cross section area, but also due to less stress concentrations and more consistent density.

Fatigue performance of various connecting rods is illustrated in Graph 1.



Graph 1. Survivable fatigue load range of connecting rods

Thanks to warm compaction, a single pressed and single sintered connecting rod can be made as light as a standard rod and with sufficient fatigue strength to match of the performance of a standard powder forged rod.

There is a possibility to remove the cross beam of the second warm compacted design since the increased width of the legs, compared to the first version, improves the buckling resistance of the shank considerably. Besides weight reduction, a consequence of such a design modification would also be a less complex compaction tool with fewer and more robust core rods.

8. CONCLUSIONS

Connecting rod prototypes have been manufactured by Warm Compaction, green machining, sintering and fracture-split

Cost savings are possible due to fewer manufacturing steps and better materials utilization compared to other manufacturing methods such as powder forging and forging

Warm compacted prototype connecting rods have been tested and compared to P/F and steel forged standard rods with respect to Survivable Fatigue Load, SFL

Warm compacted prototype connecting rods have been made as light as the forged standard rods and to a fatigue performance that matches the standard P/F connecting rod.

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