MATERIALS FOR HIGHLY LOADED PARTS SUCH AS CONNECTING RODS

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Abstract - Warm compaction offers high density, favorable pore structure and as a result of this better fatigue properties combined with the robustness and shaping ability of the established compaction technology. This means that high performing parts, such as connecting rods, cam lobes and transmission gears etc., can be produced in a cost efficient way. In this investigation different high density P/M steels are evaluated concerning fatigue strength and a comparison is also made with powder forged and conventionally forged steels. Fatigue data on specimen are used as a base for the design of a P/M connecting rod. The connecting rod used for this comparison is for a modern mass produced four cylinder 2.2 liter gasoline engine. Its design has been optimized for the P/M route in order to minimize the weight. The dynamic performance of the warm compacted prototypes is discussed and a comparison with connecting rods made by the other manufacturing techniques is made.
KEYWORDS: IRON POWDER, WARM COMPACTION, CONNECTING ROD, HIGH DENSITY, FATIGUE STRENGTH

I. INTRODUCTION

Billions of parts are produced annually 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) 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.

II. WARM COMPACTED CON ROD - DESIGN

A warm compacted prototype connecting rod (Picture 1.) for a four cylinder 2.2 liter gasoline engine was designed (Ref. 1). Characteristics for the engine, which is produced in high volumes, are given in Table 1. The weight of the currently used connecting rods for this engine is approximately 500 g each.

Table 1. Engine details

- Engine type: Gasoline
- Configuration: In-line 4 cyl.
- Bore x Stroke: 86.0x94.6 mm
- Max. firing pressure: 70 bar
- Maximum power: 100 kW@5600 rpm
- Cylinder centers: 96 mm
- Con rod centers: 146.5mm
- Crank pin diameter: 49 mm



Picture 1. Warm Compacted Prototype Connecting Rod

The prototype con 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 for this engine. The design criteria is summarized in Table 2.

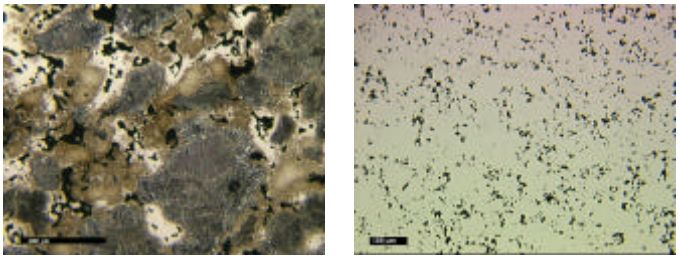
Table 2. Design criteria for warm compacted protoype con rod

- Fit existing engine
- Fatigue Safetey Factor > 1.5
- Minimized weight
- Uncomplicated Manufacturing Process

III. MATERIALS AND MATERIALS DATA

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 Distaloy HP-1 + 0.7%C. Distaloy 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-atomised powder with 1.5% molybdenum. 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 min at 1120 ^{o}C (2050 ^{o}F) in N_2-based atmosphere is listed in Table 3. The structure after sintering consists of 2/3 Martensite, 1/3 Bainite and a few percent of Austenite (Picture 2.). Processing parameters can be found under the section prototypes.



Picture 2. Metallographic structure of sintered con rod material Distaloy HP-1 (Fe , 4%Ni, 2.0%Cu, 1.5%Mo) + 0.7%C etched (left) and as polished (right)

An alternative to a high performing material can be a less alloyed powder in combination with a component design that has a larger cross-section area. The consequence of such a design is increased component weight and as a result of that larger mass-forces acting on the connecting rod. In order to make it possible to quantify the connecting rod endurance limit for a medium performing material warm compacted to high density a press ready mix of Fe-Cu-C type (ASC100.29+2%Cu +0.8%C) was also included in the study. This material has a pearlitic structure when processed under the same conditions as the Distaloy HP-1 material. The axial fatigue strength (R=-1) of this material, based on warm compacted test bars with a denisty of 7.3 g/cm3, is approximately 175 MPa. Ultimate tensile strength is 595 MPa and the yield strength is 440 MPa.

Table 3. Materials data for Distaloy HP-1+0.7% C used for design (based on compacted test bars)

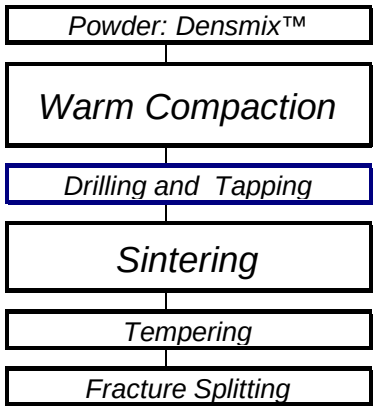
Density	7.35 g/cm^3
Poissons ratio	0.26
Young's modulus	165 Gpa
UTS	940 MPa
Yield strength	540 MPa
Compressive strength	621 MPa 1)
Axial fatigue limit (R=-1)	260 MPa
Bending fatigue limit	300 MPa

Note: 1) calculated

IV. PROTOTYPES

Prototypes were manufactured using a hydraulic press upgraded for warm compaction. Machining of the screw holes and the threads was carried out after compaction, whereas the fracture split of the big end was performed in the as sintered conditions. The processing data used for protytype manufacturing of the warm compacted rods is given in Table 5. Besides the rods made of Distaloy HP-1 a batch of connecting rods made from Fe-Cu-C material was also made and tested in order to find out how different powder materials influence the fatigue performance of connecting rods.

Table 4. Processing route for warm comapcted prototype connecting rods



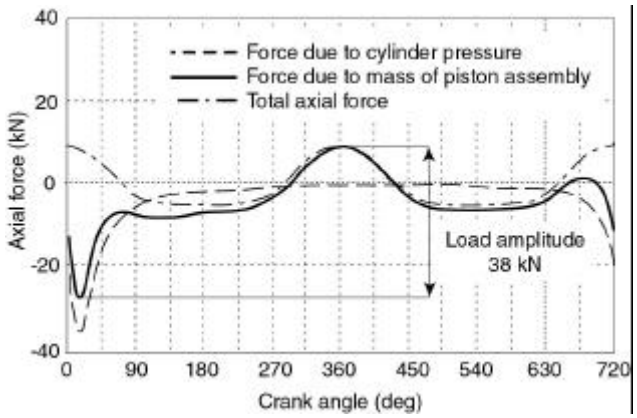
The Fe-Cu-C rods were manufactured in the same way as the Distaloy HP-1 prototypes except that the tempering was excluded. Tempering does not add any improvement of the Fe-Cu-C material properties while it can improve the fatigue performance and the ductility for the Distaloy HP-1 based material.

Table 5. Processing data for warm compacted prototype connecting rods.

Powder :	Distaloy HP+0.7%C-UF, Densmix
Compaction press:	400 tons hydraulic press
Compaction pressure	800 MPa (58 tsi)
Pressing force:	260 tons
Tool :	Steel die – 3 upper + 3 lower punches, 4 cores
Powder-/ tool temp.:	125 ^{o}C / 135 ^{o}C (260 ^{o}F / 280 ^{o}F)
Drilling of 2xØ9 mm bolt holes :	prior to sintering, feed rate 0.25 mm/r n= 3000 rpm
Threading of 2xM9:	prior to sintering feed rate 1 mm/r n=750 rpm
Sintering furnace:	Continuous mesh belt furnace
Sintering:	1120 ^{o}C (2050 ^{o}F) for 30 min, 90%N_2+10%H_2 atm., cooling 1 ^{o}C/sec (2 ^{o}F/sec.)
Tempering:	200 ^{o}C (392 ^{o}F) for 60 min. air
Fracture split -big end:	Wedge + impact

V. CONNECTING ROD LOAD

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 Graph 1.

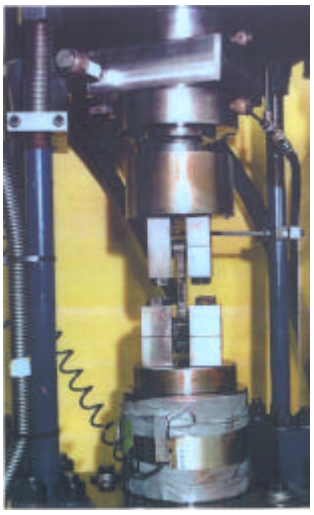


Graph 1. Connecting rod load at engine peak power

The load pattern illustrated in Graph 1 and the design criteria for the connecting rod lead to the test method described in the next section. The compression force is approximately twice the tensile force. Since the load amplitude at engine peak power is 38 kN and the minimum saftey factor is 1.5, a succesful component test must result in a run out load amplitude exceeding 57kN.

VI. TEST OF PROTOTYPES

In order to determine the survivable fatigue load finished prototype assemblys incl. bolts, bearings and bushings were tested in a rig (Picture 3) according to the stair case method. Test duration is 10 M cycles. The load case is R=-2, which means that the compression stress is twice the tensile stress. This load case is considered to be representative for a gasoline engine at peak power.

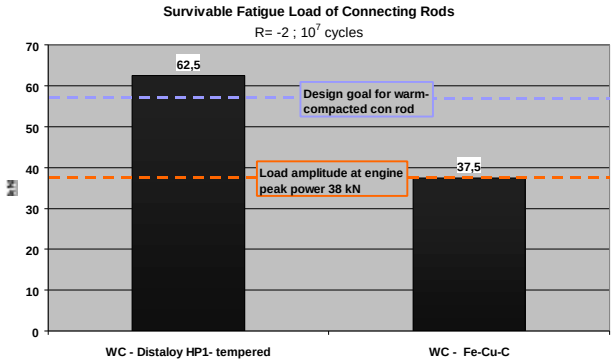


Picture 3. Fatigue test of connecting rods

Oil was introduced at the bearing surfaces in order to avoid possible fretting. The fractures of the non surviving prototypes were analyzed.

VII. RESULT

The survivable fatigue load for the warm compacted prototype rod made of Distaloy HP1+ 0.7%C is 63.5 kN, which is 63 % larger than the load amplitude at engine peak power (Graph 2). This means the design criteria having a saftey factor larger than 1.5 was met. All the failures occurred at the shank region which is desired from test point of view. A typical fracture initiation point for the warm compacted rods is located at an inner radius of the mid section of the shank. (Picture 4).
For the prototypes made of Fe-Cu-C material the survivable fatigue load was 38 kN, which is considerably lower than for the Distaloy HP-1 material. The survivable load was almost equal to the above mentioned engine load amplitude. Such a small margin is not acceptable and therefore a rod made of this Fe-Cu-C material must be re-designed in order reach sufficent safety factor. Such a re-design would involve a larger cross-section area which in turn leads to an increased component weight.



Graph 2. Survivable Fatigue Load for Con Rod prototypes

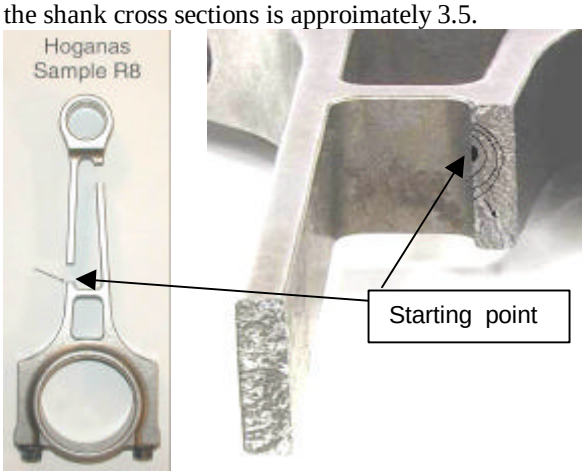
The endurance limit of the materials was determined based on the run out loads from the prototype tests, the load conditions and the cross-section area of the shank (141.5 mm^2). For the connecting rods made of Distaloy HP-1, the cyclic stress is –74 ±258 MPa and for the Fe-Cu-C material -44±132MPa . The endurance limit (s) representative for fully reversed load (R=-1) can be calculated by using Goodmans relation at zero meanstress and the ultimate tensile stress (1).

(1) $$s = \frac{s_{alt}}{1 - \frac{s_{mean}}{s_{UTS}}}$$

Table 6. Endurance limit based on con rod tests

	Endurance limit (MPa)	
	R=-2	R=-1
Distaloy HP1	258 MPa	239 MPa
Fe-Cu-C	132 MPa	123 MPa

The fractures of the non surviving samples were studied with respect to initiation. A typical fracture starts at the location shown in Picture 4. The density was somewhat lower in this region compared to the bulk section of the shank, which toghether with the stress concentration caused by the radius can explain both the location of the fracture and the fact that the connecting rods have lower endurance limit compared to the corresponding data originating from ideal test bars. The height-width ratio of the shank cross sections is approimately 3.5.



Picture 4. Location of fracture initiation of fatigue tested con rod

Based on the results of this investigation, further design improvements can be suggested in order to increase the fatigue life of the connecting rods. Increased width of the shank sections lead not only to a larger load carrying cross-section area, but also to a more favourable width-height ratio which in turn can lead to improved density distribution. Increased inner radii of the shank section can reduce the stress concentration and improve the fatigue life.

VIII. COMPARISON OF MFG METHODS

The 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. A consequence of this is high material utilization and a minimum of machining. For warm compaction the number of operations is reduced significantly compared to other manufacturing alternatives (Table 7).

Table 7. Processing of warm compacted, powder forged and forged connecting rods

	Warm Compaction	Powder Forging	Steel Forging
Number of mfg steps	13	17	16
Raw material weight	515 g	560 g	850 g
Finished rod 1)	475 g	485 g	510 g

1) Excluding bolts and bushings

IX. CONCLUSIONS

- Connecting Rod Prototypes have been manufactured by Warm Compaction, Green Machining, Sintering and Fracture-Split
- Warm compacted Prototypes have been tested with respect to Survivable Fatigue Life and the endurance limit has been determined for two powder materials
- Connecting Rods made of Distaloy HP-1 survived a load 63 % higher than the cyclic load at engine peak power
- Cost savings are possible due to fewer manufacturing steps and better materials utilization compared to other manufacturing methods such as Powder Forging and Forging.

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