Comparative Evaluations of Malleable and Ductile Iron Connecting Rods

P. GIUGNI, G. SARIETTO and G. MAGISTRALI - Teksid I.F.D., Carmagnola, Italy

Abstract

The main characteristics of pearlitic cast irons for connecting rod production are considered with regard to malleable and ductile iron alternative.

After a preliminary discussion on respective metallurgical aspects and relative process relabilities, an experimental stress analysis by strain gouge chains is described about the evaluation of conrod design respect to stress distribution optimization.

Then a number of fatigue tests (long run and one-step procedures) on both types of irons are presented with conrods wholly machined, fitted with bushes and suitably gripped by pins with the allowance effectively required in the engine, so as to realize the true conditions of fatigue material decaying.

The results are discussed, from which some better behaviour is shown by conrods of ductile iron.

Riassunto

Sono considerate le principali caratteristiche delle ghise perlitiche per bielle con riguardo alle ghise malleabili e sferoidali.

Dopo una discussione preliminare sugli aspetti metallurgici e l'affidabilità dei due processi, viene descritta l'analisi delle sollecitazioni con catene di estensimetri al fine di valutare sperimentalmente l'ottimizzazione della forma progettuale di una biella circa la distribuzione delle sollecitazioni.

Quindi sono presentate le prove di fatica (durata a vita infinita e durata a termine) effettuate su bielle di entrambi i tipi di ghisa, finite di macchina, complete di cuscinetti e montate sull'attrezzatura di afferraggio secondo le tolleranze dimensionali previste nel motore, al fine di ottenere nel corso della prova condizioni di sollecitazione analoghe a quelle alle quali è sottoposto il materiale in opera, che pongono in evidenza sensibili vantaggi di comportamento per la ghisa sferoidale.

Introduction

Cast iron has stood out for years among other materials for the production of vehicle components such as structural elements (suspension links, steering knuckles, brake components, etc.) as well as engine components, such as crankshafts and conrods.

The choice in the designing stage among the various solutions offered for a component is made by evaluating performances such as: weight/resistance ratio, fatigue resistance, etc. Furthermore, when large mass productions are implied, the economical factor plays a fundamental role.

In view of all this, cast iron is now used for the production of most conrods in the motor industry.

However, there is an alternative in this field between *malleable* and *ductile iron*.

Malleable iron is the older historically, while ductile iron was developed in the sixties and has become increasingly diffused for castings in replacement of steel forgings.

Without going further into details that go beyond the scope of this study, we can point out briefly that both above mentioned iron types are characterized by graphite precipitating in nodules or spheroids. Therefore the resistance properties of the matrix, that is pearlitic for conrods, are decidedly high and can be compared with those of structural steels.

For what the fracture mechanics is concerned, the presence of graphite nodules, substantially equivalent to tiny spherical cavities, involves some advantage because at some extent they act as a crack-stopper against the spreading of a possible microcrack.

This is true as a general consideration. However from the point of view of production, the peculiarities of both processes, that's, malleable and ductile iron production, imply some variants that might influence the behaviour of the conrod in operation.

After a short preliminary remark about the processes for the production of both types of cast iron, we are now going to describe some fatigue tests made to compare the results. Then the results will be discussed.

Preliminary remarks about malleable and ductile iron castings

It is well known that carbon is present as carbides in malleable iron castings upon solidification and, as a consequence, the metallurgical structure of the iron is extremely fragile (white cast iron). By a further thermal treatment of malleabilization around 950 °C with a 24 hours'stay in the furnace (the last hours of which are devoted to a controlled cooling) carbon separates and precipitates in its stable form, graphite. That is to say that carbides split up and carbon migrates and precipitates as graphite round nodules (Fig. 1).

When the thermal treatment is completed, malleable iron for conrods mainly consists of a pearlitic matrix with graphite nodules.

When tapping ductile iron castings, a spheroidizing agent (usually magnesium) is added. Therefore already in liquid iron some spheroidal graphite embryos start to enucleate. These embryos then will grow during solidification. The final result is a compact structure with graphite spheroids.

As before, the structure of iron for conrods has a pearlitic matrix (Fig. 2).

For what the reliability of these processes is concerned, it is important to point out that:

— For *malleable iron* there is a risk of causing cracks when removing risers or handling with the castings because of the extremely brittle structure before the malleabilization treatment. For this reason, once the treatment is over, it is necessary to make sure that the metallurgical structure is really the expected one, particularly for what graphite nodules and the absence of residual carbides are concerned.

Among others, a banal, but not negligible risk, is the possibility of mixing untreated conrods with the treated ones during the routine handling.

Apart from the usual metallurgical checks, a magnetic particle control to detect any cracks as well as a magnetic gauge sorting for thermal treatment evaluation are generally required.

— *Ductile iron* has the advantage to obtain the final structure directly upon casting, with neither risks of cracks nor any need for a thermal treatment.

On the other hand, a non-destructive control of the suitable degree of spheroidization of graphite is necessary. It should be made sure that the addition of magnesium (as iron alloy) has been sufficient to obtain the required degree of graphite spheroidization to avoid the harmful presence of any traces of sharp edge graphite lamellae).

Actually this can be caused by a fading effect, if the casting times are too long (addition of magnesium in the ladle or in the converter) or if the quantity of magnesium has been insufficient because of a malfunction in the casting line (in-mould magnesium addition).

Ductile iron hardly has any risk of cracks because there is no fragile structure phase to go through during the process.

Test program

To optimize the performances of a conrod, specific for a given engine, the experimental analysis of the stress distribution by strain-gauge is appropriate. It is a direct check of the finished product complete with pin, bearing and cap, to reproduce the actual static loading conditions. In this way, in comparison with the project reckoning, i.e., the finished part sizing according to reckoning, considerable improvements can be obtained in terms of perforances/weight ratio with slight local shape modifications. For what the preparation of fatigue tests is concerned, first a series of grips must be made to apply the conrod the dynamic loads in a way most congruous with the actual stresses the part undergoes during operation in the engine, for instance by reproducing the coupling tolerances considered in the project (both interference and play). The load is usually axial, in push and pull.

To the purpose of this study the fatigue tests have been carried out respectively:

— To determine the fatigue resistance limit to compare the behaviour of the two iron types in the long run (therefore for infinite life).

— To evaluate the dispersion of the resistance after a given limited endurance to verify the influence of process variables and the reliability that can be obtained with conrods in the two iron types.

Sample preparation

— *Malleable iron QS 11 MS 65*
35 finished conrods were available with pins fixed, according to the regular production process.

Composition

C_t%	Si%	Mn%	Cu%	Sn%	S%	Ni%	Cr%	Mo%	P%
2.78	1.33	0.46	0.09	0.010	0.105	0.05	0.03	0.01	0.15

Microstructure (Fig. 1)

graphite nodules
pearlitic matrix
hardness 229 HB

— *Ductile iron GH 65-48-05*
38 finished conrods were available with pins fixed as above.

Composition

C_t%	Si%	Mn%	Cu%	Sn%	S%
3.68	2.45	0.24	0.74	0.005	0.007

Microstructure (Fig. 2)

Degree of graphite spheroidization:	90 ÷ 95%
Ferrite around the nodules:	10 ÷ 15%
Rest	pearlite
Hardness	262 ÷ 269 HB

Both groups of conrods had the same shape, as illustrated by Fig. 3. In particular, the minimum sections in the stem were equivalent, within the limits of precision tolerance on the raw surface.

Static tests

The shape of the conrods has been optimized taking account for the suggestions from the preliminary static measurements with strain-gauges, as illustrated by Fig. 3. The test showed the strains with push-pull axial loading, making sure that the actual coupling conditions obtained on the engine were effectively reproduced at the grips.

Fatigue tests

1) Test preparation

Fatigue tests were carried out with an electrohydraulic MTS system 458-20 by applying a push-pull axial load with a cycle ration $R = -1.84$. This value is a compromise result of the calculation of the inertial forces due to the dynamic masses and the maximum pressure acting on the piston at the various speeds of rotation (for example Fig. 4 shows a graph of the pressure inside the cylinder, measured at 6100 rpm with local stresses measured by strain-gauge directly by the engine test at the bench, [ref. 1]).

Fig. 5 shows the detail of the conrod with grips; the pin is tightened, with interference allowance according to the specified values, and fixed to the bottom fork rigidly; the big eye complete with halfbearings and cap with screws tightened with a controlled torque, is coupled with the top fork pin with play according to project.

During the test, the bearing was lubricated statically to ensure a fluid film as it happens in operation.

2) Fatigue resistance tests

This test has been programmed to obtain an S/N graph (Woehler's curve). In view of the limited quantity of conrods available, a few of them, which were unbroken after the "stair-case" test, were reused for the low-cycle fatigue field, but only for the highest load levels. On the other hand the reverse slope of the S/N curve was known "a priori" from the data-base bank of CRF (Research Center of FIAT) for both types of tested cast-iron.

The fatigue resistance limit was determined at max. 4×10^6 cycles.

The S/N graph for malleable iron is shown by Fig. 6.

Table 1 shows the "stair-case" table with values 10 to 90% of survival level.

For ductile iron the analogous results are shown by Fig. 7 and Table 2.

3) One-step tests

For fatigue tests with a limited endurance duration the same instruments have been used.

The cycle ratio has been kept as above: $R = -1.84$ and the alternate load amplitude has been adopted in such a way as to obtain average breakage lives from 2 to 8×10^5 cycles.

According to the S/N curves obtained before, the following load cycles have been applied:

- malleable iron: -10.36 ± 36 kN
- ductile iron: -11.98 ± 40.5 kN

Fig. 8 shows the graph of the breakage life distribution for both iron types and the results are given in Table 3.

Discussion of the results

By observing the microstructure it is possible to see that the graphite spheroids in ductile iron (Fig. 2) are mainly spherical with a sharp delimitation of the smooth metal surface, while for malleable iron (Fig. 1) graphite is present in nodules with a rather irregular metal surface around them, with many sharp edges that, in principle, contribute to intensify the local stresses. The "stair-case" fatigue test, carried out with a max. test duration of 4×10^6 cycles, with pushpull stress and cycle ratio $R = -1.84$ has allowed to obtain the following results:

Malleable iron QS 11 MS 65

Fa 50 = 33.5 kN (50% survival)
Fa 90 = 29.9 kN (90% survival)
s = 3.6 kN (standard dev. estimate)

Ductile iron GH 65-48-05

Fa 50 = 37.2 kN (50% survival)
Fa 90 = 32.0 kN (90% survival)
s = 5.2 kN (standard dev. estimate).

TABLE 1 - Stair-case results for malleable iron conrods

TEKSID I.F.D. - Product Development Program: STCASEIN
Report No.: Date of the Report:

FATIGUE TEST - Stair case method

Component: connecting rod
Material: malleable iron
Date of the test:
Stressing mode: push-pull cycle ratio: R = − 1.84
Max. number of cycles: 4000000
No. of points: 14 No. of points valid for the statistics: 0

Fa	Order number of the specimens																							
kN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	i	ni	ini	ˆ 2 nni
40.5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6	0	0	0
39.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5	0	0	0
37.5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4	0	0	0
36.0	–	–	–	–	–	–	–	–	–	–	–	R	–	R	–	–	–	–	–	–	3	2	6	18
34.5	–	–	R	–	R	–	–	–	–	–	O	–	O	–	–	–	–	–	–	–	2	2	4	8
33.0	–	O	–	O	–	R	–	–	–	O	–	–	–	–	–	–	–	–	–	–	1	1	1	1
31.5	O	–	–	–	–	–	R	–	O	–	–	–	–	–	–	–	–	–	–	–	0	1	0	0
30.0	–	–	–	–	–	–	–	O	–	–	–	–	–	–	–	–	–	–	–	–	0	0	0	0
28.5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	0	0	0
27.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	0	0	0

R: Failed specimen O: Not failed specimen

6	11	27
N	A	B

DATA of the STAIR-CASE TEST

Spec. No. -	No. of cycles	Notes
1 –	4000000	–
2 –	4000000	–
3 –	2000000	– breakage in the stem
4 –	4000000	–
5 –	1843000	– breakage in the stem
6 –	1725000	– breakage in the stem
7 –	1026000	– breakage in the lubrication hole
8 –	4000000	–
9 –	4000000	–
10 –	4000000	–
11 –	4000000	–
12 –	650000	– breakage in the stem
13 –	4000000	–
14 –	1783000	– breakage in the stem

Fatigue strength

Fa50 = 33.5 kN (mean value at 50% level of survival)
Fa10 = 37.1 kN (value at 10% level of survival)
Fa90 = 29.9 kN (value at 90% level of survival)
s = 2.84 kN (standard deviation estimate)

TABLE 2 - Stair-case results for ductile iron conrods

TEKSID I.F.D. - Product Development Program: STCASEIN
Report No.: Date of the Report:

FATIGUE TEST - Stair case method

Component: connecting rod
Material: ductile iron - GH 65-48-05
Date of the test:
Stressing mode: push-pull cycle ratio: R = – 1.84
Max. number of cycles: 4000000
No. of points: 14 No. of points valid for the statistics: 0

Fa	Order number of the specimens																							ˆ 2
kN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	i	ni	ini	nni
45.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6	0	0	0
43.5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5	0	0	0
42.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4	0	0	0
40.5	–	–	–	–	–	R	–	R	–	–	–	–	–	–	–	–	–	–	–	–	3	2	6	18
39.0	–	–	–	–	O	–	O	–	R	–	–	–	–	–	–	–	–	–	–	–	2	1	2	4
37.5	–	–	–	O	–	–	–	–	–	R	–	–	–	–	–	–	–	–	–	–	1	1	1	1
36.0	R	–	O	–	–	–	–	–	–	–	R	–	R	–	–	–	–	–	–	–	0	3	0	0
34.5	–	O	–	–	–	–	–	–	–	–	–	O	–	O	–	–	–	–	–	–	0	0	0	0
33.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	0	0	0
31.5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	0	0	0
																						13	20	50
																						N	A	B

R: Failed specimen O: Not failed specimen

DATA of the STAIR-CASE TEST

Spec. No. -	No. of cycles	Notes
1 –	3755000	– breakage in the stem
2 –	4000000	–
3 –	4000000	–
4 –	4000000	–
5 –	4000000	–
6 –	940000	– breakage in the stem
7 –	4000000	–
8 –	2557000	– breakage in the stem
9 –	2727000	– breakage in the stem
10 –	752000	– breakage in the stem
11 –	1362000	– breakage in the stem
12 –	4000000	–
13 –	3586000	– breakage in the stem
14 –	4000000	–

Fatigue strength

Fa50 = 37.6 kN (mean value at 50% level of survival)
Fa10 = 42.2 kN (value at 10% level of survival)
Fa90 = 32.9 kN (value at 90% level of survival)
s = 3.67 kN (standard deviation estimate)

TABLE 3 - One-step fatigue conrod test results (summary)

MATERIAL	ENDURANCE	[cycles]
	50% survival (average)	90% survival
Malleable iron	764962	347734
Ductile iron	1605902	635811

For one-step tests, the loading levels for the two iron types have been different, to obtain lives possibly ranging from 0.5 to 2×10^6 cycles.

After a few attempts and in view of the dispersion areas of S-N graphs (Fig. 6, 7) the already mentioned stress cycles were applied, still with a stress ratio $R = -1.84$. Therefore the results of the one-step test have been as follows:

Malleable iron QS 11 MS 65

Loading cycle: -10.36 ± 36 kN (Fmax = + 25.64 kN
Fmin = − 46.36 kN)
Average life: 764962 cycles (50% survival)
347734 cycles (90% survival)
Standard dev. estimate: 10.7%

Ductile iron GH 65-48-05

Loading cycle: -11.98 ± 40.5 kN (Fmax = + 28.52 kN
Fmin = + 52.48 kN)
Average life: 1605902 cycles (50% survival)
635811 cycles (90% survival)

Stair-case tests show a higher level of the fatigue limit for ductile iron with an increase of 7% (at a survival level of 90%). If we take the average values the increase would be 11%.

For one-step tests the increase in favour of ductile iron goes up as high as 83% at the survival level of 90% (109% if we take the average values) even if it has been submitted to a much more severe loading cycle.

The highest fatigue resistance limit for ductile iron can be attributed to the structure of the matrix and to the ferrite halos around the graphite spheroids, that might act as a crack stopper [ref. 2] as well as to the smoother and more regular form of the spheroids in comparison with the malleable iron nodules.

In the "one-step" test, malleable iron life proved decidedly shorter, despite th elower loading levels. This can presumably be attributed mostly to th euneveness of the nodules, where the presence of sharp edges causes a considerable intensification of the stresses with a local plasticization effect.

Conclusions

The behaviour of malleable and ductile iron conrods type GH 65-48-05 has been compared experimentally by means of fatigue tests under dynamic loading.

Both materials were tested directly as mechanical components, making sure that the loads applied (grips, stress cycles) were as congruous as possible with the real loads. Both the resistance tests to fatigue in the long run (4×10^6 cycles) and the "one-step" test have given better results with ductile iron type GH 65-48-05.

Bibliography specific references

[1] P. Giugni, G. Magistrali, G. Sarietto, *Acquisition of Strain and Stress data from Connecting Rod During the Crankshaft Revolution under Variable Load and Speed*, Teksid - Isata, 22° Int. Symposium on Automotive Technology and Automation, Florence, (1990).

[2] A. Cionchi, F. Daglio, P. Comani, *La tenacità delle ghise malleabili a cuore nero e sferoidali*, Falck - La Fonderia Italiana, 6 (1982).

General bibliography

- R. Roncato, A. Blarasin, *Applicazione del criterio della banda di dispersione unificata all'analisi del comportamento a fatica di acciai da bonifica e di ghise sferoidali*, Centro Ricerche Fiat - IX Convegno Nazionale dell'Associazione Italiana per l'Analisi delle Sollecitazioni, (Settembre 1983).
- M. Castagna, P. Ferrero - Centro Ricerche Fiat, R. Medana, E. Natale - Teksid - Div. Alluminio, *Fatigue Properties of In-mould Ductile iron*, AFS Transactions 78-84, p.p. 573-582.
- E. Di Carlo, M. Ricciotti, *Esame delle caratteristiche di resistenza a fatica della ghisa sferoidale per un ulteriore sviluppo degli impieghi automobilistici*, Fiat Auto - Laboratori Centrali, XVIII Congresso di Fonderia, (Giugno 1986).
- L. Wilhelm, *Cast iron. A ductile material for high Loaded Components*, George Fischer Limited, Switzerland Report.

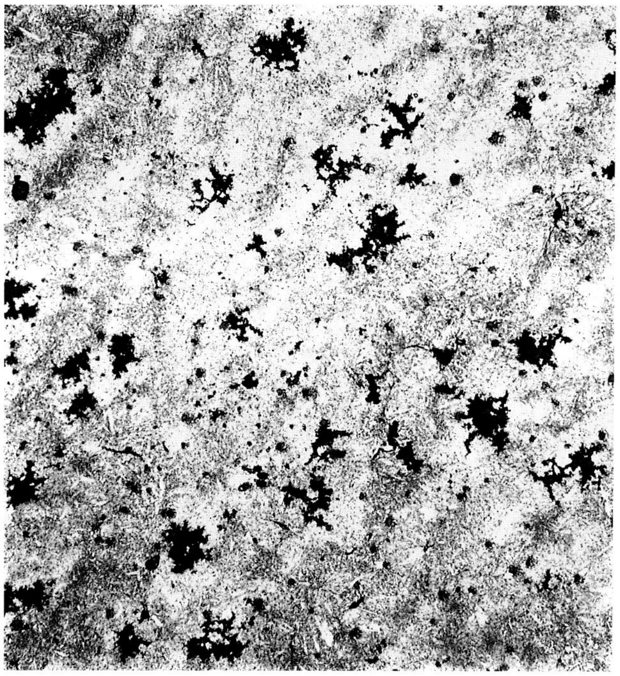


Fig. 1:
Metallurgical structure of malleable iron conrod (× 50).

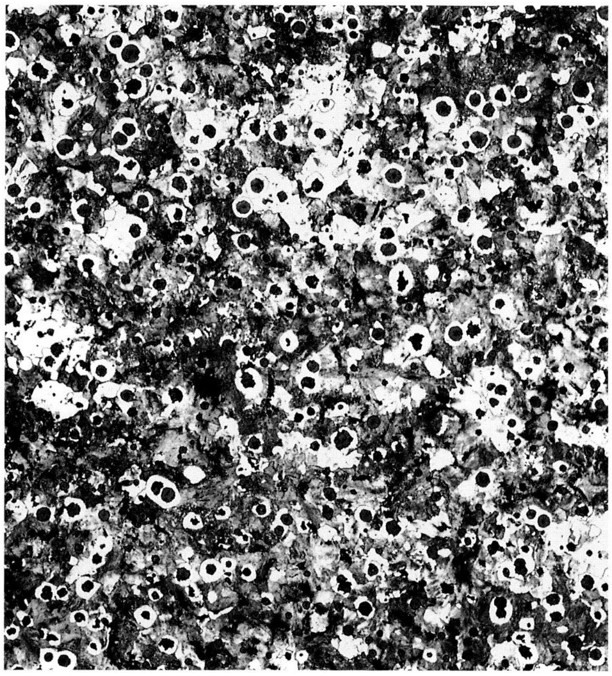


Fig. 2:
Metallurgical structure of ductile iron conrod (type GH 65 48 05) (× 50).

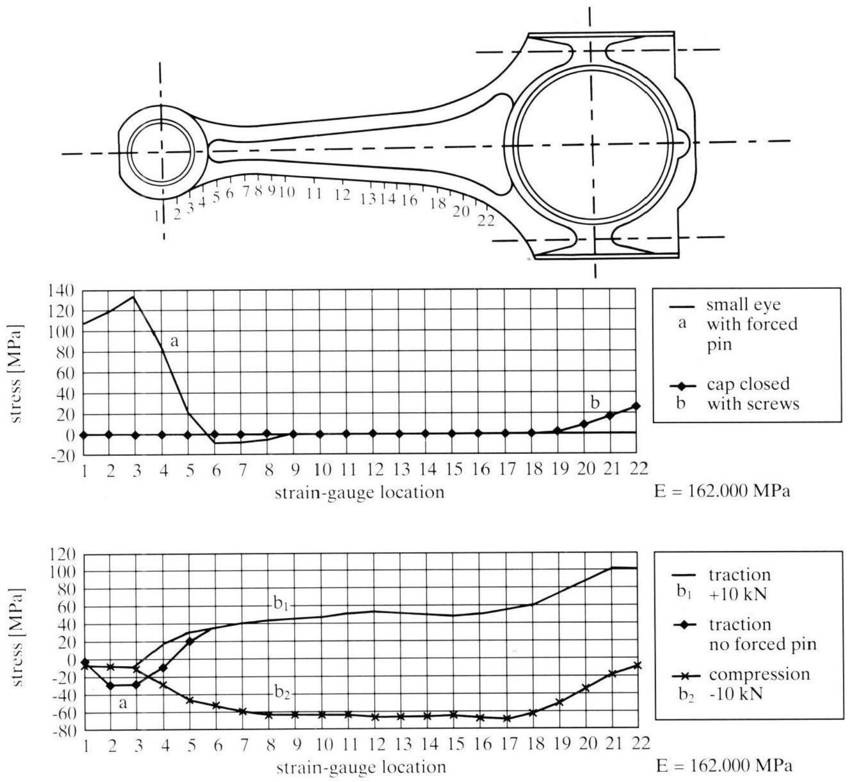


Fig. 3:
Static stress analysis at various points of the conrod by means of strain-gauge-chains. Push-pull loading.

6100 min^{-1} – extra-speed test without load.

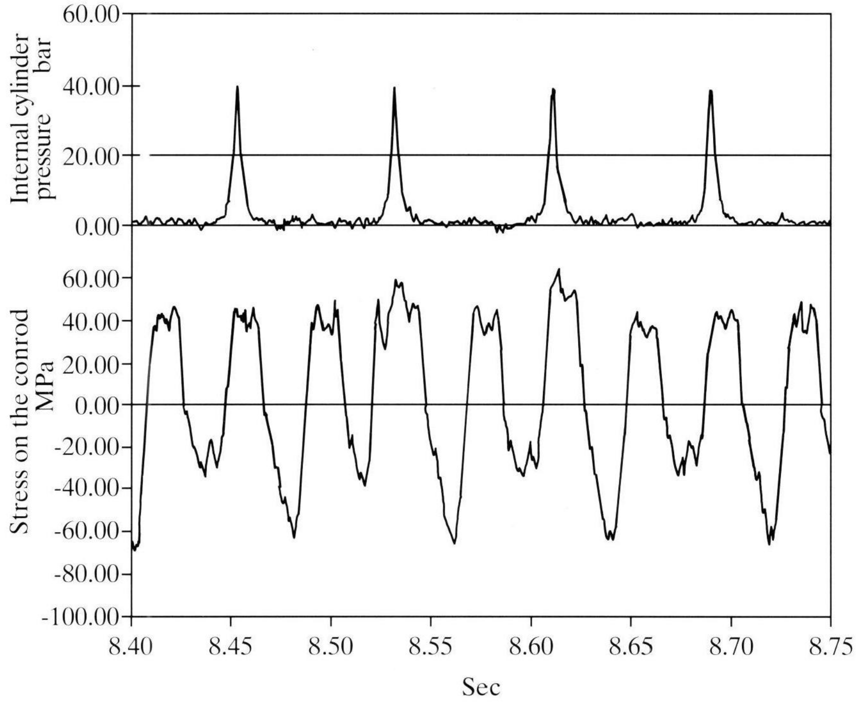


Fig. 4 a):
Internal cylinder pressure and istantaneous stress on the conrod obtained by strain-gauge during the engine bench test.

Expanded sygnal - 2 channels.

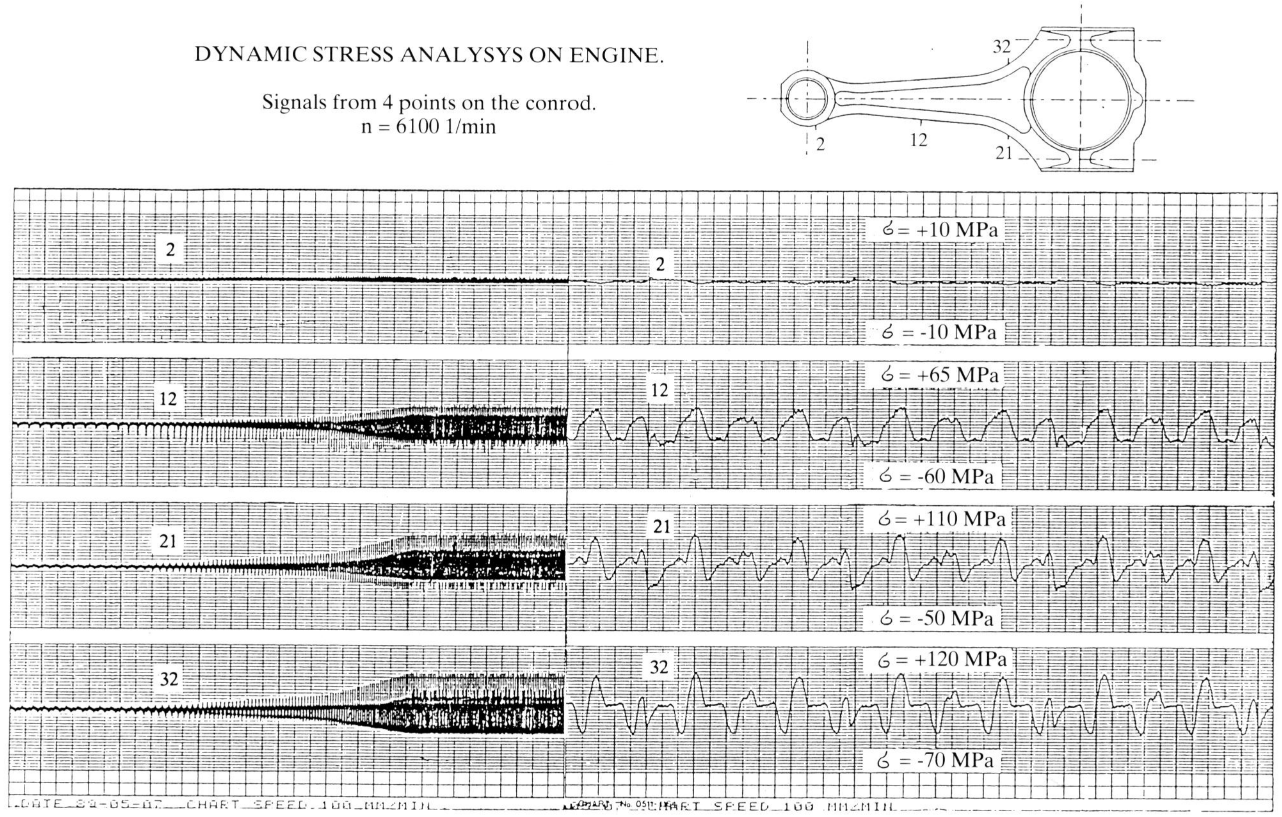


Fig. 4 b):
Internal cylinder pressure and istantaneous stress on the conrod obtained by strain-gauge during the engine bench test.

Complete engine speed range. Compressed and expanded sygnals - 4 channels.

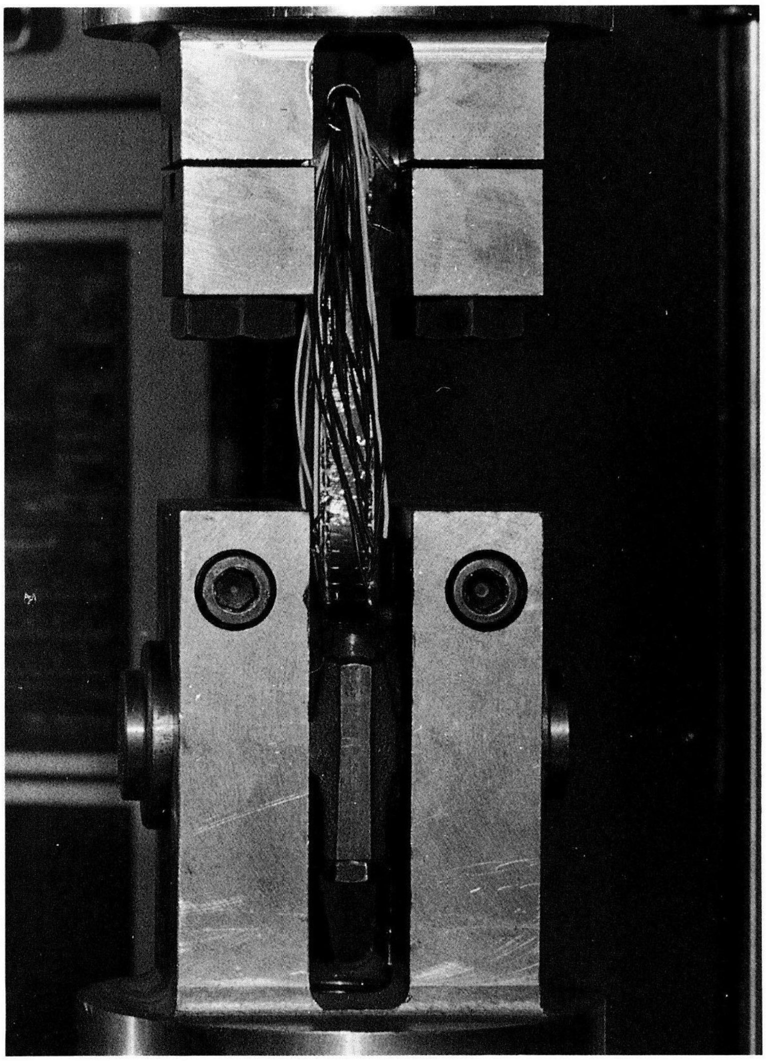


Fig. 5:
Conrod with the two grips (the conrod is gauged).

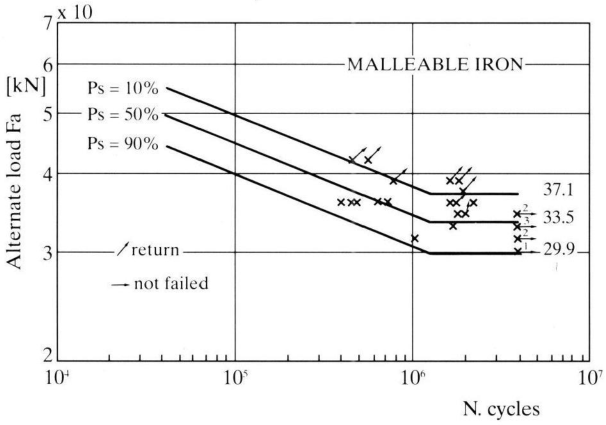


Fig. 6:
Malleable iron. Stair-case table and S-N graph.

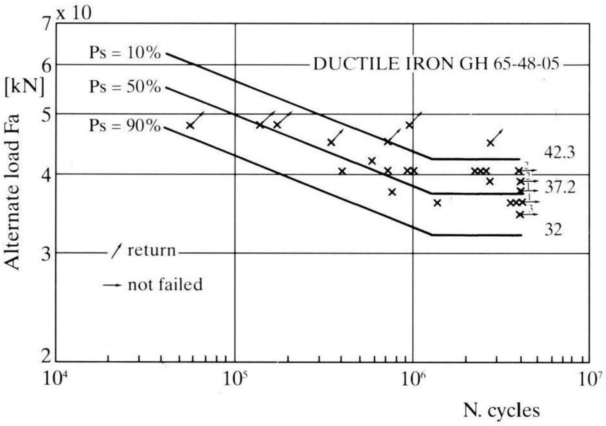
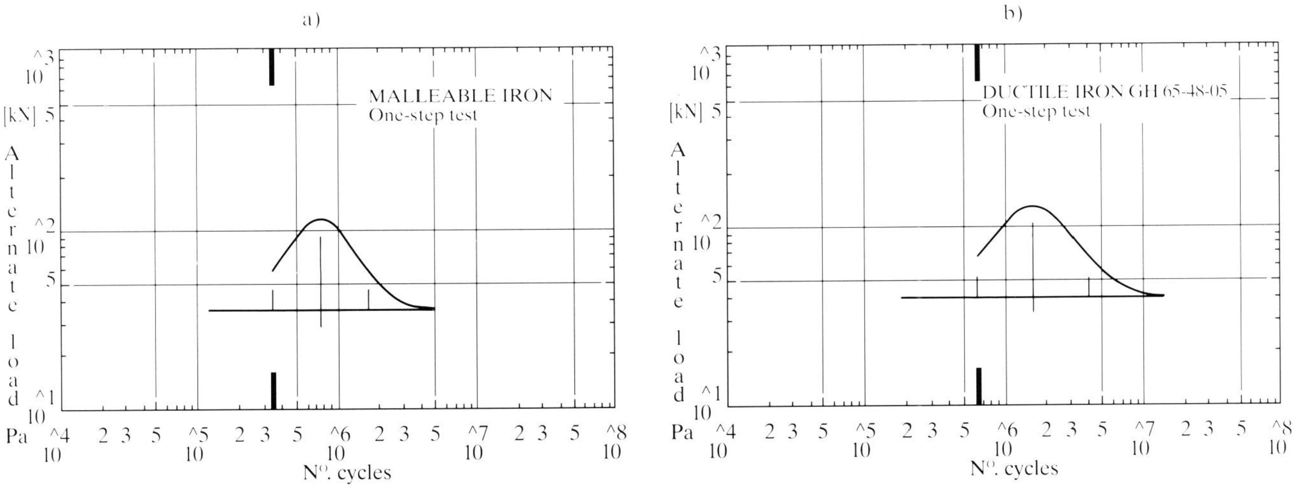


Fig. 7:
Ductile iron grade GH 65 48 05. Stair-case table and N-S graph.

 a) b)

REPORT: DATA:
Component: CONNECTING ROD - malleable iron
Notes: Low cycle fatigue - ONE-STEP test

LOAD LEVEL ACTUAL [kN]	N°. CYCLES ACTUAL	N°. CYCLES NORMALIZED	LOAD LEVEL of REFERENCE [kN]
36.00	650000	650000	36
36.00	2224000	2224000	36
36.00	409000	409000	36
36.00	484000	484000	36
36.00	1690000	1690000	36
36.00	458000	458000	36
36.00	738000	738000	36

Inverse slope of Woehler curve in the low cycle fatigue range: -8.97

ENDURANCE (50% survival) : 764962 cycles
ENDURANCE (90% of survival) : 347734 cycles

REPORT: DATA:
Component: CONNECTING ROD - ductile iron GH-65-48-05
Notes: Low cycle fatigue - ONE-STEP test

LOAD LEVEL ACTUAL [kN]	N°. CYCLES ACTUAL	N°. CYCLES NORMALIZED	LOAD LEVEL of REFERENCE [kN]
40.50	940000	940000	40.5
40.50	2557000	2557000	40.5
40.50	2377000	2377000	40.5
40.50	2252000	2252000	40.5
40.50	2230000	2230000	40.5
40.50	3862000	3862000	40.5
40.50	3923000	3923000	40.5
40.50	1011000	1011000	40.5
40.50	715000	715000	40.5
40.50	400000	400000	40.5

Inverse slope of Woehler curve in the low cycle fatigue range: -8.97

ENDURANCE (50% survival) : 1605902 cycles
ENDURANCE (90% of survival) : 635811 cycles

Fig. 8:
One-step test. Graph and summary table.