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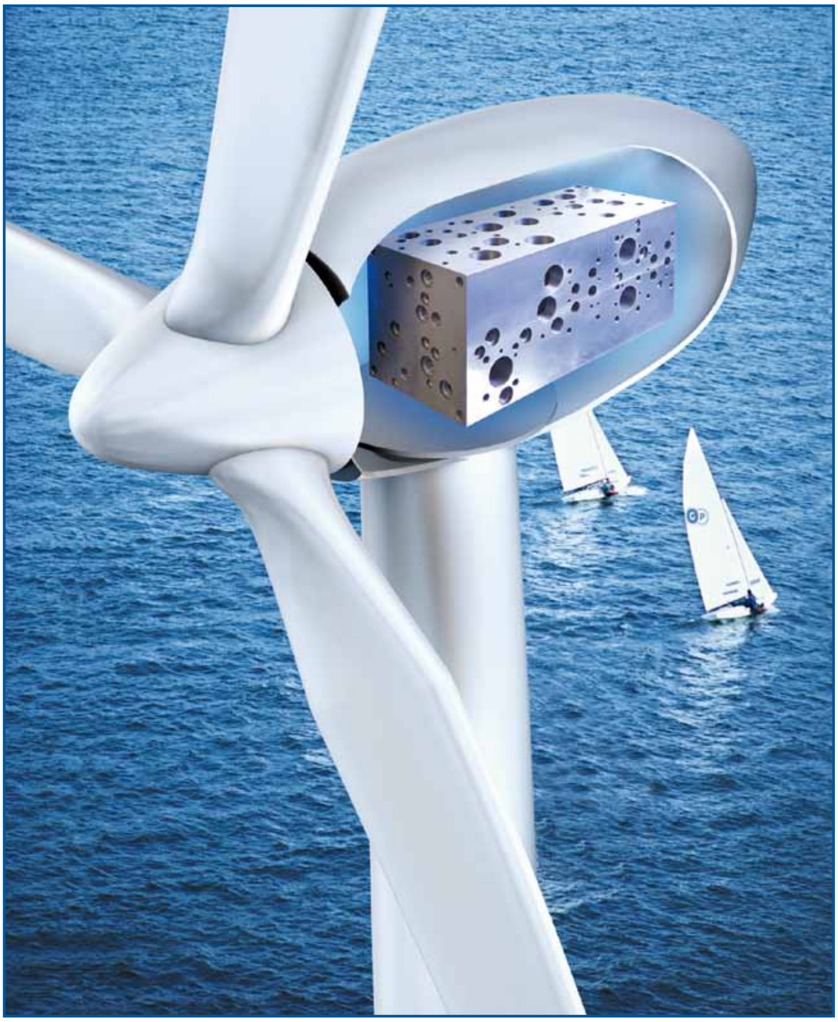
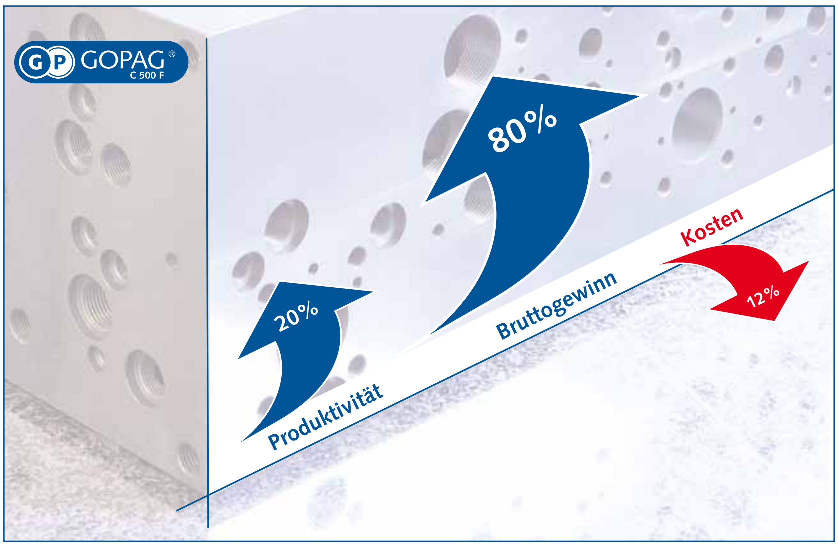
Burst Pressure Tests with Cast Iron Materials at Low Temperatures

1 Introduction

For a long time, various grades of cast iron have proven themselves in hydraulic, fluid and mechanical engineering. With rising working pressures and/or other increasing requirements, first GJL grades (grey cast iron) and then mainly GJS materials (cast iron with nodular graphite, also known as spheroidal graphite cast iron), mostly EN-GJS-400-15 or EN-GJS- 400-18, were used. Metalworkers value these materials, which evidence substantially improved values for elongation, yield strength, and tensile strength, in comparison with steel. This is due above all to significantly improved cutting performance as well as substantially improved tool service life during complicated machining. Since a few years ago, the latest generation of cast iron materials, high-silicon GJS qualities, has come into use for stresses that exceed the limits of EN-GJS-400 and in situations in which, among other things, the loss in elongation of EN-GJS-500-7U due to its microstructure makes it inadequate for the intended applications [1]. With mechanical properties that are in no way inferior to those of various types of steel used in hydraulics and mechanical engineering, this purely ferritic cast iron stands out because of excellent machinability with minimal tool wear [2]. **Fig. 1**. In the constantly expanding sector of off-shore applications, but also in the maritime sector, there is growing interest in the use of high-silicon cast iron materials such as Gontermann-Peipers' GOPAG® C 500 F. At present, however, there are still obstacles standing in the way of widespread use of these materials. These include the regulations and standards of the classification societies, which seldom include cast iron materials, as well as a lack of knowledge about modern cast iron materials in general. This is compounded by the fact that little is known at present about the behaviour of this second generation of cast iron materials at low temperatures.





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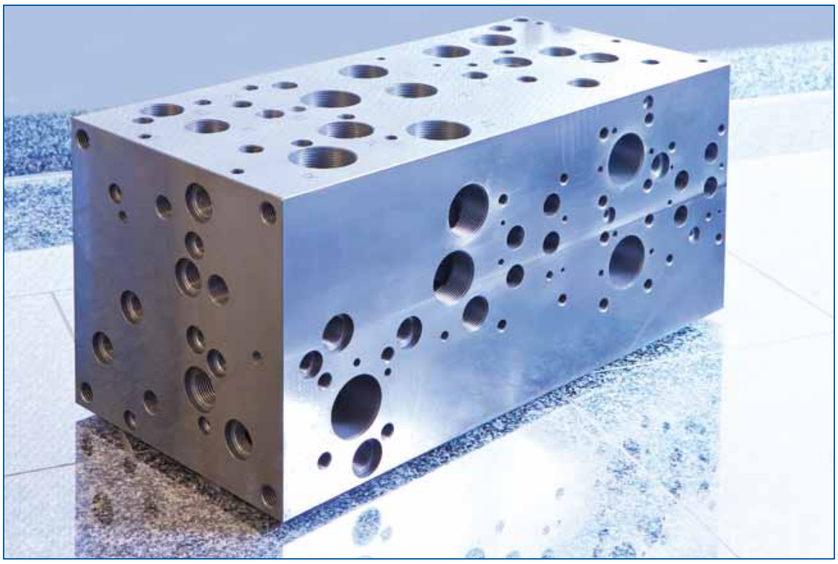
Notched Bar Impact Values for Cast Iron Materials

Notched bar impact work is a simple testing procedure that was developed more than one hundred years ago. The use of small, plain samples and the relative simplicity and speed with which testing can be carried out permit cost-effective determination of values. For the material GJS-400-18U-LT at -20 °C, EN DIN 1563 requires an individual value of 7 J and a mean value from 3 tests of 10 J notched bar impact work with a wall thickness of 60 to 200 mm as minimum values. Most designers still have these values committed to memory from their university days. They stand for the widespread misconception that cast iron materials in general are brittle and cannot be used at low temperatures. Many still recall pictures of sunken World War II liberty ships and other major loss events as cautionary examples. Brittle fractures of welds in cold waters made designers acutely sensitive to the low-temperature impact resistance of materials. The notched bar impact test, which is frequently used in this connection, establishes a minimum of 27 J at 20 °C for cryogenic structural steel. Thus it unjustifiably downgrades cast iron with the aforementioned, substantially lower notched bar impact strengths. The valid notched bar impact test standard EN DIN 10045 does nothing to change this general view of matters. On the other hand, it is a little known fact that notched bar impact work results are comparable only within a uniform group of materials.



Thus structural steel and cast iron, as well as alloyed grades of steel, cannot be compared with one another on the basis of an identical notched bar impact test [9]. Because the notched bar impact work is also not directly applicable to component calculation, each designer must decide for him- or herself which other tests/values are required for a specific component design [9].

The Concept of Fracture Mechanics

Besides the determination of strength and elongation values, fracture mechanics also offers additional possibilities. The concept of facture mechanics quantitatively combines permissible stress components and the sizes of structural discontinuities to express a new material property, fracture toughness. This material property denotes the resistance to instable crack propagation [8]. Thus the fracture toughness value determined for the material constitutes an important criterion when it comes to component design. Testing of the GOPAG® and Hyt 60 materials at the University of Aachen resulted in identical KIC values for both materials [1]. At present, additional tests are being conducted at the TU Bergakademie Freiberg for the drafting of a standard for continuously cast iron, so that designers will have verified values at their disposal in future. The standard EN DIN 1563 2011 contains additional informational appendices for GJS materials. However, practical tests, if conducted using appropriate safety factors, can frequently also make it possible to draw conclusions about component design.

2 Materials Tested

A bursting pressure test conducted at HYDAC Fluidtechnik in September 2010 (GOPAG® C 500 F in comparison with 11SMnPb30+C) demonstrated that, at room temperature, the cast iron material is able to withstand a higher pressure than the high speed steel [3]. The test rig showed that the threads on the connector were stripped at approx. 5,000 bar with both materials. In this situation, Gontermann-Peipers decided to conduct its own bursting tests at room temperature, -20 °C, and -40 °C on three spheroidal graphite cast iron materials and one alloyed forged steel that has been optimized for use in the hydraulics industry.

The materials compared were:

- high-silicon GOPAG® C 500 F (continuous cast), an EN GJS-400-15U (continuous cast),
- EN-GJS-400-18 (chill cast ingot casting), which is listed and approved by the DNV [11], among other organisations,
- HYT 60 (alloyed forged steel).

GOPAG® C 500 F clearly surpasses HYT 60 in terms of yield strength and in particular A-elongation. As anticipated, however, both GJS 400 materials are inferior to GOPAG® and the forged steel in terms of strength and hardness. Typically for high-silicon materials, GOPAG® C 500 F evidences a yield strength ratio significantly higher than that of the other materials **(Table 1)**.

All Gontermann-Peipers cast materials evidence a practically purely ferritic microstructure with cleanly defined and finely distributed spheroid graphite particles which permit machining at high cutting speeds and lead to minimal tolerances. In GP's accredited laboratory, it was established that the structure of HYT 60 evidences an extremely high perlite content **(Table 2)**. A comparison with other tested samples of this grade of forged steel [1, 2, 4], however, indicated a generally wide range of fluctuation in microstructure and breaking elongation. However, the manufacturer of this material also does not state a guaranteed breaking elongation in the material data sheet.

Mechanical properties of the materials tested

	Position of the sample in the block	Tensile strength R_m	Yield strength Rpo,2	Yield strength ratio Rpo,2 / R_m	Breaking elongation A 5	Hardness
		(Mpa)	(Mpa)		%	HB
GOPAG® C 500 F	1/4 D	**495**	**385**	**0,778**	17,0	**180 - 181**
GJS-400-18U-LT	außen	377	242	0,641	26,0	123 - 137
GJS-400-15U	1/4 D	402	269	0,670	23,5	142 - 144
HYT 60	außen	**560**	**345**	0,610	6,5	**180 - 184**

Table 1

		Basic structure			Graphit (nach EN ISO 945)		
		Ferrit	Perlit	Zementit	Form	Size	Degeneration
GOPAG® C 500 F	1/4 D	100 %	0	0	V VI	6 7 (8)	Keine
GJS-400-18U-LT	30 mm von außen	100 %	0	0	V VI	5 6 7 8	Keine
GJS-400-15U	1/4 D	98 %	2 %	0	V' VI	(4) 5' 6	Keine
HYT 60	30 mm von außen	20 %	80 %	0	-	-	-

Table 2

3 Conducting the Tests

Suitable facilities for the bursting tests were found at MAXIMATOR GmbH in Nordhausen/Harz. With the objective of not exceeding a bursting pressure of 6000 bar and for lack of a standardized test or test specimen for bursting tests, a cylindrical sample form with a wall thickness of 3 mm and a = 14 mm was defined based on the tensile strength/ bursting pressure relation according to Boardmen [5] and taking optimal sample mounting into account **(see Fig. 1)**.

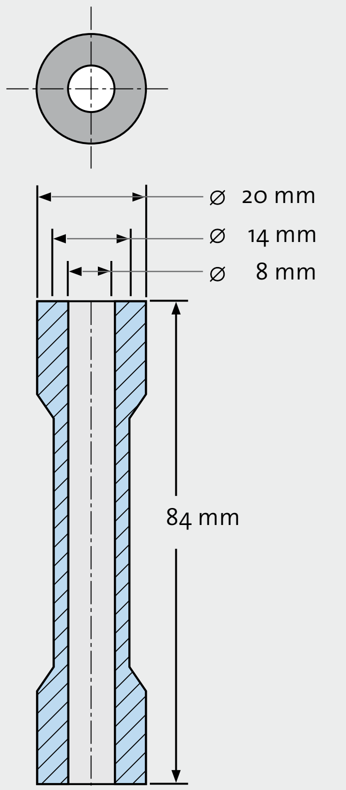


Fig 1

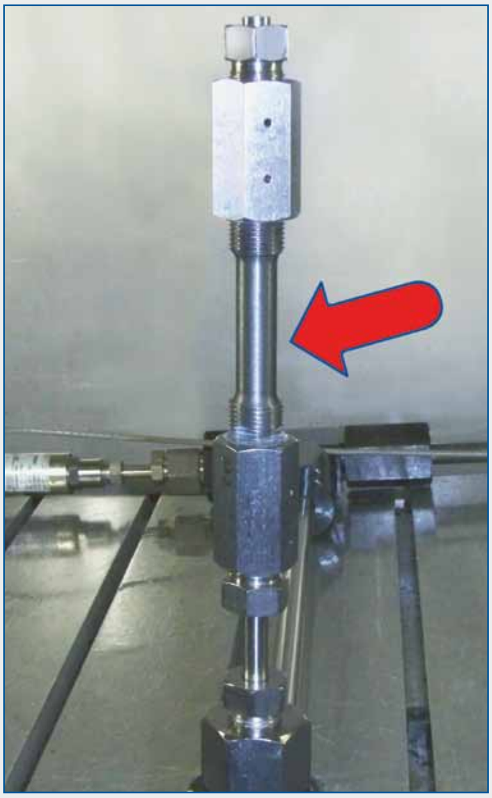


Fig 2

One end of the sample was sealed with a ball. Pressure was introduced via a press-fitted steel cone. The necessary sealing force was produced using union nuts. The test assembly in the PS 912 auto-frettage system is shown in **Figs. 2 and 3**.

Fig 3

The test conditions were defined as follows:

Test bench:	PS 912 auto-frettage tester
Test temperature:	+ 22 °C / -20°C / -40°C
Test medium:	Maxifluid
Measuring equipment:	Pressure sensor Wika 7000 bar, N524700001
Test specifications	
Pressure curve:	Inlet pressure: 1.000 bar
Pressure increase:	170 bar/s.

The pressure increase of 170 bar/s is intended to simulate a static load. The inlet pressure of 1000 bar served to stabilize the system before the actual loading.

4 Results

All three materials (GJS 400, GOPAG®, forged steel) displayed varying bursting behaviour at the respective test temperatures. Whilst GOPAG® C 500 F, due to the low elongation range above the yield strength, evidences an extremely low permanent deformation and bursts, the traditional, ferritic GJS materials evidence permanent deformation before bursting. The behaviour of HYT 60 changes significantly depending on the test temperature. As already demonstrated in other tests as well, [7] all of the materials evidence a slight temperature-dependent change in mechanical properties, which is reflected in the deformation before bursting **(Fig. 4)**. Unlike GOPAG® 500 and HYT 60 (in this case, only at -40°C), the GJS 400 evidence a permanent plastic deformation.

GOPAG® C 500 F

RT

- 20 °C

- 40 °C

GJS 400-18U-LT

RT

- 20 °C

- 40 °C

GJS 400-15U

HYT 60

Fig 4

As anticipated, the bursting pressures established during the tests were equivalent to the previously determined tensile strengths. Except for GOPAG® C 500 F, all of the materials evidenced a slight increase in pressure as temperature declined **(Table 3)**.

Bursting pressures at various temperatures

EN-GJS-400-15U			EN-GJS-400-18U-LT			GOPAG® 500 GJS			HYT 60		
22 °C	- 20 °C	- 40 °C	22 °C	- 20 °C	- 40 °C	22 °C	- 20 °C	- 40 °C	22 °C	- 20 °C	- 40 °C
2469	2563	2856	2324	2447	2544	2857	2926	2973	3763	3864	4070
2482	2609	2912	2269	2447	2449	3112	2901	2919	3755	3911	4100
-	2607	2871	2287	2461	2458	2986	2914	3139	-	3636	3963

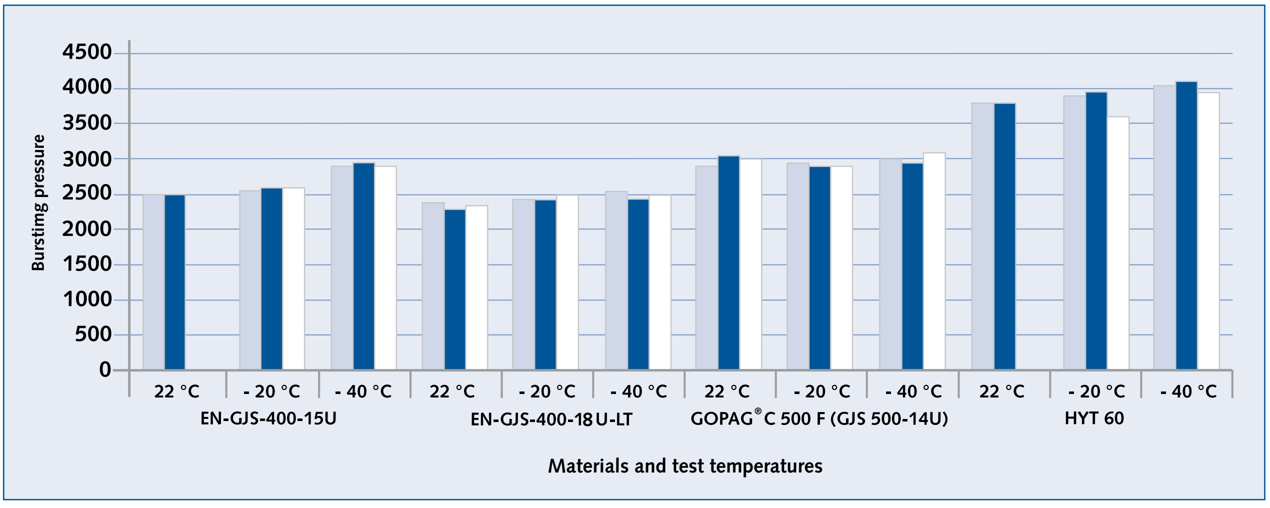
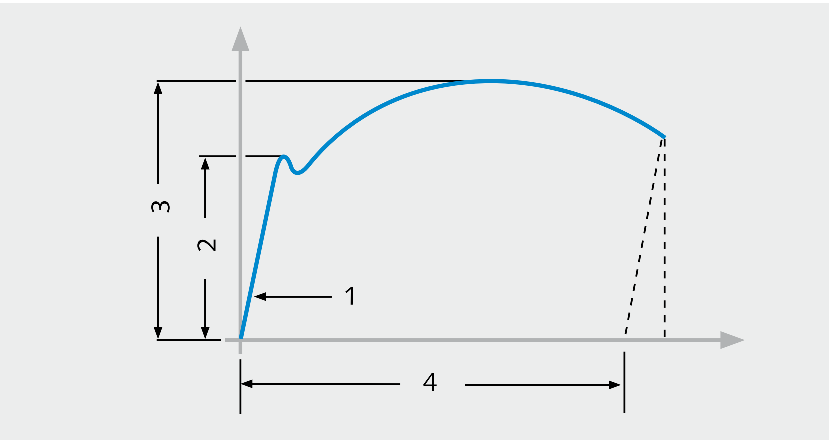


Table 3

5 Practical Implications

In evaluating the bursting pressures determined in the biaxial (planar) stress condition, the question arose of the extent to which these can be viewed directly in relation to the results of the tensile test in the uniaxial stress condition. With the help of a calculation of the tensile strength from the bursting pressure according to Boardman [5], however, a good correlation resulted for the cast iron materials with +17 % to +19% in comparison with the values in **Table 1**. In this connection, the steel evidenced a deviation of +30%. One main cause for the deviations was thought to be the short length of the test pipe, since all calculations using the aforementioned formulas assume an infinitely long test pipe. In any event, in comparison with the formulas of Barlow and Lame [5], the results according to Boardman showed the greater correlation with the measured values in **Table 1**. All of the values calculated were lower than the results of the tensile test, with an increasing tendency for the deviations to increase with declining temperature, which again confirms the findings reported in [9]. Consequently, the information below includes an additional safety factor =/ > 17%. Correspondingly, it was decided to forego the determination of equivalent stresses with the help of an otherwise separately applicable strength hypothesis. The calculated yield strength ratios $R_{p\,0,2}$ / R contained in **Table 1** were used correspondingly for calculation of a theoretical yield strength for the selection of materials. (**Table 4**, **Fig. 5** [6]). Cast iron materials evidence higher values for tensile strength and yield strength, in approximately the same proportion, as temperatures decline. Thus it was possible to use the same yield strength ratios for all temperatures investigated [9, 10].



1 HOOKE's law

2 Yield strength $R_{p\,0,2}$

3 Tensile strength R_m

4 Braking elongation A

Fig 5

Yield strength / tensile strength ratio

Material	$R_{p\,0,2}/R_m$
GOPAG® C 500 F	0,778
GJS-400-18U-LT	0,641
GJS-400-15U	0,670
HYT 60	0,610

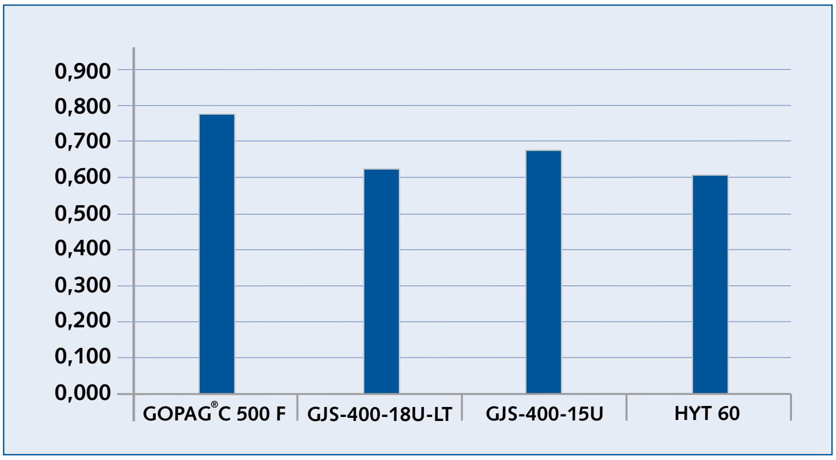


Table 4

The yield strengths determined as the product of yield strength ratio and bursting pressure ($R_{p\,0,2}$ / R x P bursting pressure) **(Fig. 5)** show the actual parameters that are essential for the designer when evaluating the materials (Table 5). They describe the respective maximum pressure, as a function of temperature, with which the materials can be loaded without this resulting in a permanent deformation.

Yield strength ratio x bursting pressure as an equivalent of yield strength

EN-GJS-400-15U			EN-GJS-400-18U-LT			GOPAG® C 500 F			HYT 60		
22 °C	- 20 °C	- 40 °C	22 °C	- 20 °C	- 40 °C	22 °C	- 20 °C	- 40 °C	22 °C	- 20 °C	- 40 °C
1654	1717	1914	1490	1569	1631	2223	2276	2313	2295	2357	2483
1663	1748	1951	1454	1569	1570	2421	2257	2271	2291	2386	2501
-	1747	1924	1466	1578	1576	2323	2267	2442	-	2218	2417

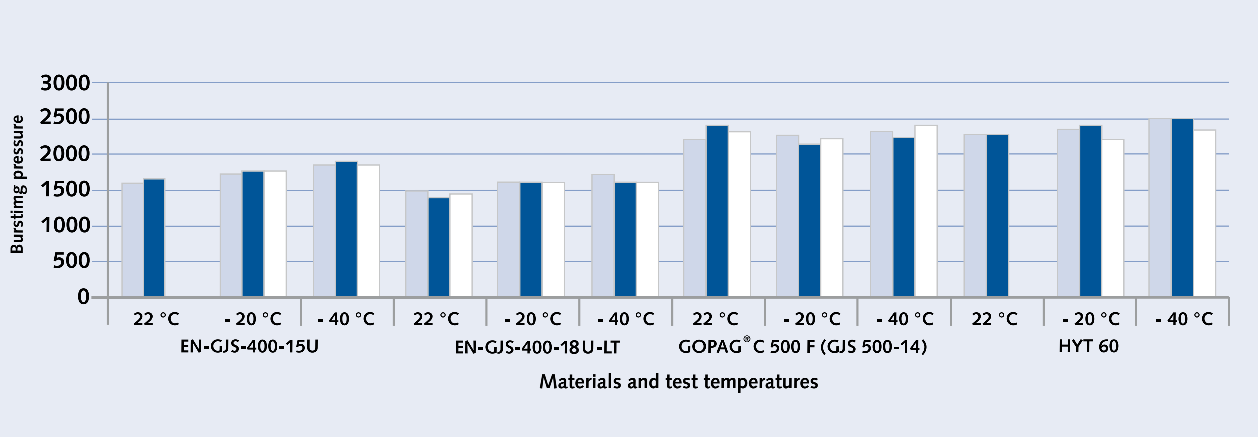
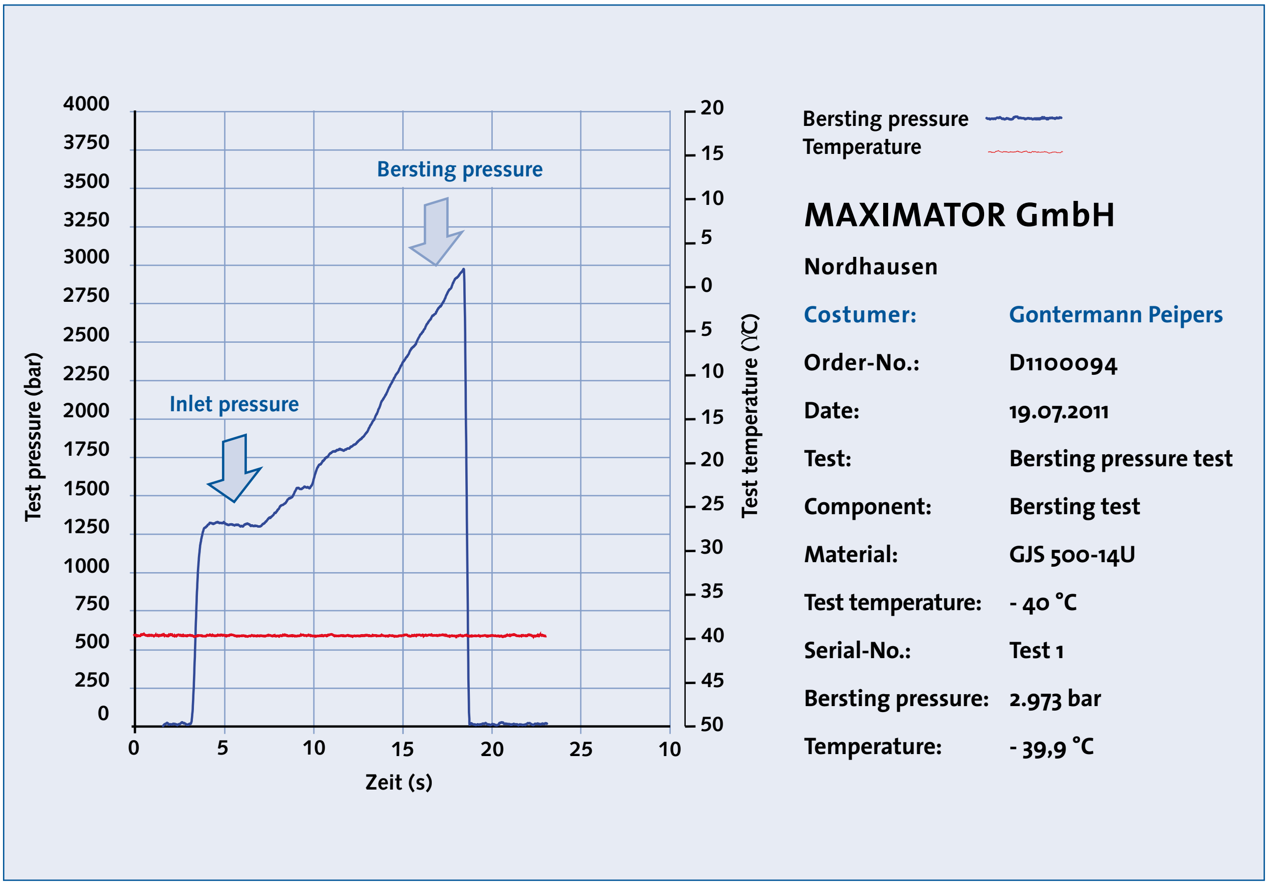


Table 5

Over the entire temperature spectrum, GOPAG® C 500 F attained a mean yield strength of **2310 bar**. With a safety factor of 3 and a wall thickness of 3 mm, this results in a maximum nominal pressure of 770 bar or 924 bar with an "S" of 2.5. For a normal 250-bar application, this means a safety factor of 9.2, thus providing substantial reserves for the designer.



6 Summary

All of the materials tested evidenced no significant fluctuations in the test at Rm and $R_{p\,0,2}$.

The bursting tests showed that all three spheroidal graphite cast iron materials can also be used at cryogenic temperatures, e.g., for hydraulic blocks.

Under test conditions, the only material in the series of tests which is classified for use at -20°C, EN-GJS-400-18U-RT, does not differ significantly from the other materials tested.

Of all of the materials tested, GOPAG®C 500 F evidences the greatest consistency of mechanical properties in alltemperature ranges, attaining values that are comparable with those of HYT 60.

The negative influence of low temperatures, which causes the notch impact strength of cast iron materials to vary sharply from that of steel, was not demonstrated in the bursting test. Inasmuch, again the question arises of the extent to which evaluation of other material properties, e.g., yield strength or fracture mechanics, would constitute a more practically oriented assessment of suitability for use at cryogenic temperatures that notched bar impact testing does. No risk was demonstrated in connection with the use of GOPAG® C 500 F at cryogenic temperatures. Thus the economic advantages of using this material, as demonstrated in [2], are also available in the off- shore and maritime sector.

Once again – as was already the case in the transition from forged to cast crankshafts – the series of practical tests conducted point up the opportunities which modern cast iron materials offer designers. In conjunction with the outstanding properties of cast iron during machining, this results in innovative solutions that can make a major contribution to cost reduction in terms of total cost.

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