Nodular Cast Iron for New Generation of Piston Engines Produced From 3D Printed Cores

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ABSTRACT

The piston engine is one of the most critical components of the automotive industry due to cyclical stresses they are subjected to. In order to adapt to new environmental legislations, the material selection for the manufacture of piston engines become even more challenging. Nodular cast iron (NCI) is a sustainable option for piston engines. Its mechanical properties can be successfully manipulated through heat treatment to achieve tensile strengths as high as 1400 MPa when austempered and 900 MPa when normalized. In addition, the use of additive manufacturing, producing cores in 3D printers, allows greater freedom of design and the production of components with few geometric restrictions. In this work, mechanical, physical and microstructure properties at high temperatures of an EN-GJS-800-02 NCI alloy were evaluated. Results have shown that thermal conductivity of this material reaches a maximum value of 31 W/Km at 400 °C, the usual working temperature of ICE components. The yield tensile strength results are as follows: 909 MPa at 20 °C and 731 MPa at 400 °C. The fatigue strength limit is 305 MPa at 20 °C and 214 MPa at 400 °C. The aim of this work was to provide a reliable data base for designers, allowing them to apply NCI for the new generation of piston engines in a more favorable way.

INTRODUCTION

The piston engine is one of the most critical components of the automotive industry due to cyclical stresses they are subjected to. Among the main properties required by piston engine, the following stand out: thermal fatigue strength, mechanical strength, heat resistance and a desirable lightweight material.

Efforts must be made to make engines even more efficient to meet new environmental legislation. The development for new emission legislation is normally combined with higher peak cylinder pressures or increased demands in power output for a better economy. In order to adapt to future demands, the material selection for the manufacture of piston engines become even more challenging. [1] [2] [3]

Although aluminum is widely used in piston manufacturing, it presents low mechanical properties that are not compatible with the new generation of high-performance engines. A second material option is steel. However, steel pistons are produced by forging, a process that involves geometric limitations. The difficulty of producing complex geometries with thin walls results in heavier parts, which further increases the challenge of ensuring an ecologically sustainable solution. [4] [5] The third option for piston engines is nodular cast iron (NCI), which presents higher mechanical strength compared to aluminum. Its mechanical properties can be successfully manipulated through heat treatment to achieve tensile strengths as high as 1400 MPa when austempered (EN-GJS-1400-1) or 900 MPa when normalized (EN-GJS-900-2). In contrast to forged steel, NCI casting process allows the production of complex geometries with thin walls, which ensures the production of lighter parts.

Figure 1 compares fatigue strength of typical alloys for piston engines.

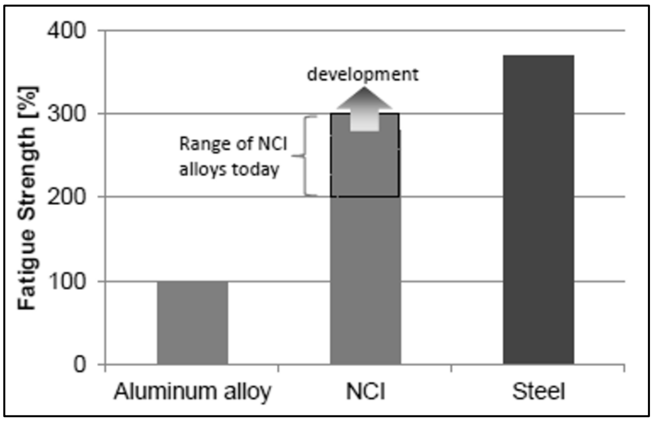

Figure 1. Comparative fatigue strength. [6]

Regarding fatigue strength, NCI can reach three times or more the fatigue strength of aluminum alloy. With proper alloying elements and heat treatment, the mechanical properties of NCI can be improved, reaching properties close to steel alloys. [6] [7]

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In addition to metallurgical conditions, product design can also contribute to the best application of this material for piston engines. The use of additive manufacturing, producing cores in 3D printers, allows greater freedom of design and the production of components with few geometric restrictions.

Although NCI is a possible material for piston engine manufacturing, the available literature related to this topic is, so far, very theoretical. There is a lack of quantitative data to put into discussion the cast iron selection to produce piston engines.

This work presents the nodular cast iron as a viable material for the new generation of piston engines produced from 3D printed cores. Thereby, NCI Y-blocks and piston engine test specimens were characterized and analyzed. The goal was to create a reliable database for the project engineer, encouraging the application of NCI pistons in engine manufacturing.

EXPERIMENTAL PROCEDURES

The research of this work was carried out using the structure, resources, products, tools and laboratories of Tupy SA foundry, based in Joinville/Brazil, BDG laboratories, based in Düsseldorf/Germany and ÖGI laboratories, in Austria.

The object of this study was a nodular cast iron class EN-GJS-800-2 piston, produced using 3D printed cores. This is a 2,2 kg piston for a 6,7L engine, with 45,5 mm on skirts, 112 mm on diameter and 4,5 mm minimum wall thickness. The additive manufacturing allows a greater freedom of design than the traditional coldbox method, making it possible to produce parts with more complicated geometry, since it is not necessary to include tooling extraction angles on the cores. Because of the small width of the piston walls, the alloy characterization had to be performed using test pieces taken from separate Y-blocks.

A batch of 52, 1” Y-blocks, with dimensions according to Table 1 and Figure 2, was cast in the same alloy and submitted to the same heat treatment cycle (normalized - 870ºC for 2 hour and cooled in air) as the pistons to obtain test pieces in proper dimensions for mechanical properties characterization. Before proceeding with the mechanical tests of the Y-block test specimens, a comparison of the mechanical and microstructure properties was performed, demonstrating that the Y-block material characteristics are representative of the piston properties.

Table 1. Y-block dimensions.

Region	Dimension (mm)
a	25
b	55
c	40
d	140
e	20
f	20

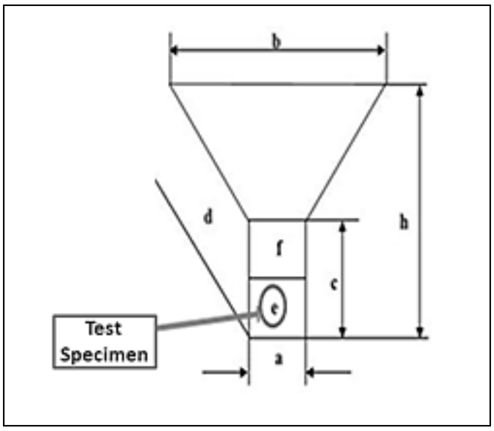

Figure 2. Y-block test specimen.

The regions of test specimens taken from the piston are shown in Figure 3.

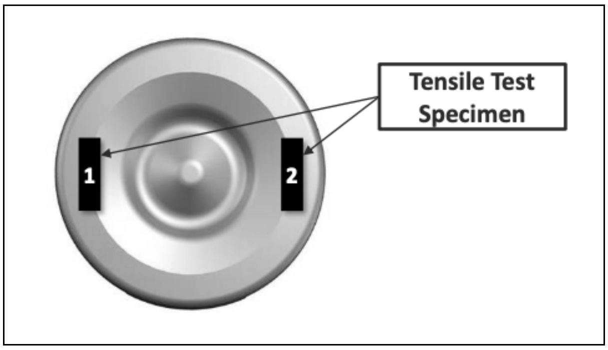

Figure 3. Test specimens taken from the piston.

Tensile test specimens taken from the piston were machined to 4 mm diameter in accordance with the standard DIN 50125:2009-07.

The chemical composition of this alloy is typical of NCI class EN-GJS-800-2, as shown in Table 2.

Table 2. Chemical composition.

%C	%Si	%Sn	%Cu	%Mn
3,53	2,72	0,018	0,574	0,25

For this study, the following tests were performed: tensile test at room temperature, 200 ºC, 400 ºC, 450 ºC and 500 ºC; high cycle rotating-bending fatigue at room temperature and 400 ºC; thermal conductivity and thermal expansion at room temperature, 100 ºC, 200 ºC, 300 ºC, 400 ºC, 500 ºC and 600 ºC and microstructure analysis.

Tensile test specimens taken from Y-blocks were machined to 10 mm diameter according to ISO 17025:2018. For each temperature, three specimens were analyzed. Tests were performed at BDG laboratories (Düsseldorf/Germany).

High cycle rotating-bending fatigue test was performed in accordance with the standard DIN EN ISO 6892-2:2018.

Tests were performed at BDG laboratories (Düsseldorf/Germany). The strain ratio was -1 for all tests. The staircase method was employed to determine the fatigue strength limit, considering runouts at 10^7 cycles.

Thermal conductivity was calculated from thermal diffusivity of the sample, which was determined by the laser-flash method. The rear face of the specimen is rapidly heated by laser and the temperature development at the front surface is measured. Thermal diffusivity is calculated from the temperature rise time and the specimen thickness, considering thermal radiation and the laser pulse-length. The thermal expansion of the specimen was determined by double-pushrod dilatometry. Measurements were made with a dilatometer of NETZSCH, Selb, Germany, Type 402CD/4/G. Tests were performed at ÖGI laboratories (Leoben/Austria).

Microstructure characterization was performed analyzing the percentage of nodular graphite and percentage of pearlite in the matrix. It was performed according to the standard: ISO 945-4:2019. Tests were performed at Tupy SA laboratories (Joinville/Brazil). To evaluate possible degradation of pearlite, some samples were kept at 500 ºC in a heating furnace and microstructure analysis were performed after 1, 3, 5 and 7 hours of heating time.

Hardness tests were performed using a Wolpert machine, with a 5 mm ball and 750 kgf load. Tests were performed at Tupy SA laboratories (Joinville/Brazil), according to the ISO 6506-1:2014 standard.

RESULTS AND DISCUSSION

The results and discussion about the development of this work were divided as follows: Results of tensile test, Results of fatigue test, Results of thermal conductivity and thermal expansion, and Results of microstructure analysis.

TENSILE TEST – Results showed that mechanical properties of Y-block and piston specimens were equivalent (Table 3).

Table 3. Mechanical properties of Y-blocks and pistons.

Sample	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
Piston – n.1	876	523	5,35
Piston – n.2	870	498	5,80
Y-block	891-937	522-546	7,6-8,7

These results validate the use of Y-blocks for analysis and characterization of the proposed material for pistons manufacturing. The purpose of this comparison is to facilitate the material analysis process in industry, in view of the small useful area for taking samples directly from pistons.

The next results presented in this work are related to the specimens taken from Y-blocks.

Tensile tests results at different temperatures are shown in Figure 4, 5 and 6.

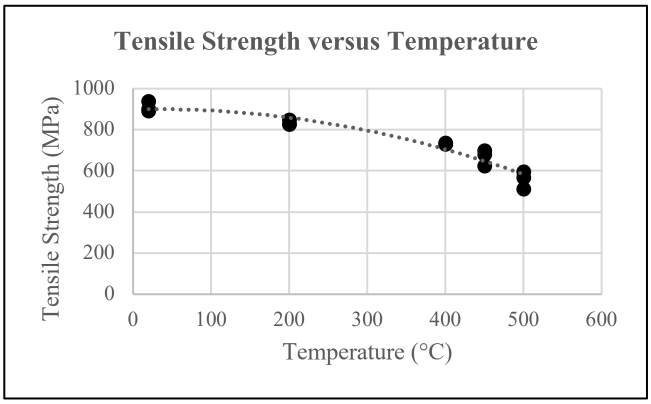

Figure 4. Tensile strength results.

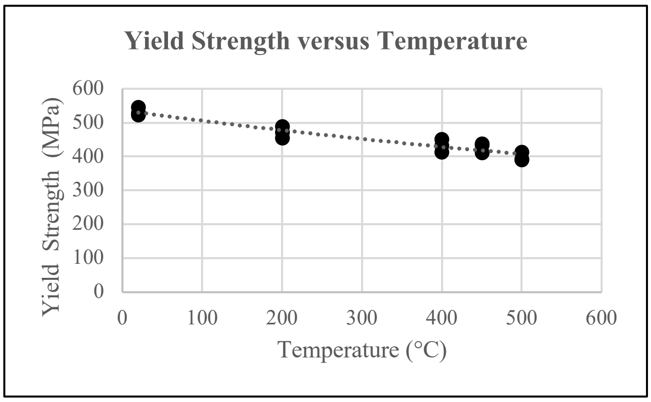

Figure 5. Yield strength results.

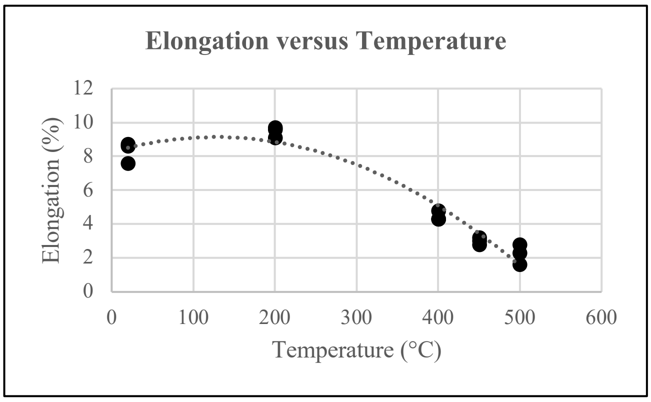

Figure 6. Elongation results.

Table 4 shows the average results of tensile tests. Ultimate tensile strength results show a drop rate of around 50 MPa/100 ºC till 400 ºC. At higher temperatures, an increase in the drop rate is seen to around 175 MPa/100 ºC. The drop rate of yield strength does not show the same behavior, it was almost constant in the temperature range tested, of around 30 MPa/100 ºC. This means that at 400 ºC, the tensile strength is around 80% of the original room temperature value, and around 60% at 500 ºC.

Table 4. Tensile test results.

Temperature (ºC)	U.T.S. (MPa)	Y.S. (MPa)	Elong. (%)
RT	908	532	8,3
200	833	471	9,5
400	731	432	4,5
450	665	423	3,0
500	556	398	2,2

The results found for this work are in line with data from the literature. For nodular cast iron, the resistance decreases continuously with increasing temperature, being more pronounced at higher temperatures. This reduction is more accentuated in pearlitic than in ferritic NCI, mainly for tensile strength results [8]. However, the pearlitic matrix is necessary for piston development due to the minimum resistance required for this type of application.

FATIGUE TESTING – Figure 7 shows the S-N curve for the rotating-bending fatigue test at room temperature and at 400 ºC.

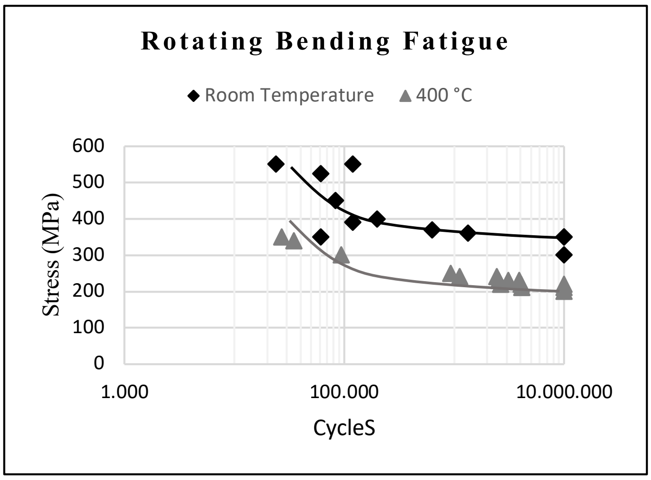

Figure 7. Fatigue test results.

The fatigue strength limit, at the survival probability of 90%, calculated through staircase method is 305 MPa at room temperature and 214 MPa at 400 ºC. This corresponds to 70% of the original value at Room Temperature. The endurance ratio at Room Temperature is 0,34 and 0,29 at 400 ºC. This means that the drop in fatigue strength related to temperature is higher than the drop of the tensile strength.

Compared to other materials normally used for piston engines, aluminum and steel, NCI presents intermediate values of fatigue strength. The variation of fatigue strength under reversed bending stress limit with temperature for aluminum alloy 4032, steel 4140 and the NCI from the present study is shown in Figure 8.

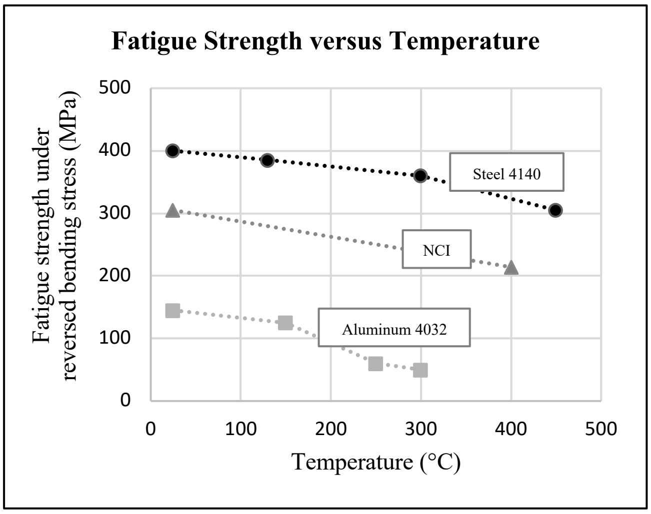

Figure 8. Comparison of fatigue strength for steel 4140, NCI and aluminum alloy 4032 (Adapted from [9]).

The comparison results indicate that NCI should be used in intermediate applications between aluminum and steel alloys. Aluminum is applied in piston engines with low mechanical strength requirements and steel piston is more suitable for heavy-duty piston engines. For medium-duty engines, when steel would be an oversized material and aluminum doesn't reach the properties required, nodular cast iron is a favorable material to be selected.

THERMAL CONDUCTIVITY AND THERMAL EXPANSION – Figure 9 shows the evolution of thermal conductivity according to temperature. At room temperature, thermal conductivity is 25,5 W/mK showing progressive increase until reaching the highest result of 31 W/mK at 400 ºC, usual working temperature of ICE components. Above this temperature, the thermal conductivity has slightly reduced.

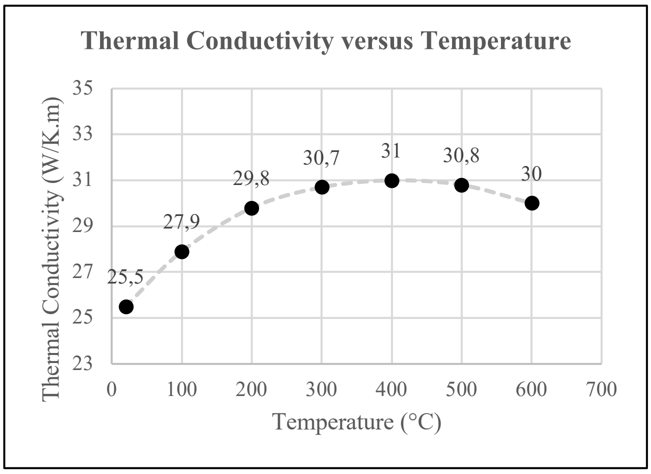

Figure 9. Thermal conductivity results.

Table 5 presents the physical properties of normalized NCI samples taken from Y-blocks.

Table 5. Physical properties results.

Temperature (°C)	Heat Capacity (J/gK)	Thermal Expansion (%)	Thermal Conductivity Calculated (W/Km)
20	0,475	0,000	25,5
100	0,516	0,092	27,9
200	0,559	0,216	29,8
300	0,596	0,354	30,7
400	0,643	0,500	31,0
500	0,704	0,652	30,8
600	0,794	0,805	30,0

MICROSTRUCTURE – Figure 9 shows the typical microstructure of an EN-GJS-800-2 alloy, with graphite nodules and a pearlitic matrix, with some ferrite around the graphite nodules and at the boundaries of the eutectic cells. As expected, there was no damage in graphite nodules at higher temperatures. The ferrite content increased only from 5 to 10% when submitted to 500 ºC for 7h.

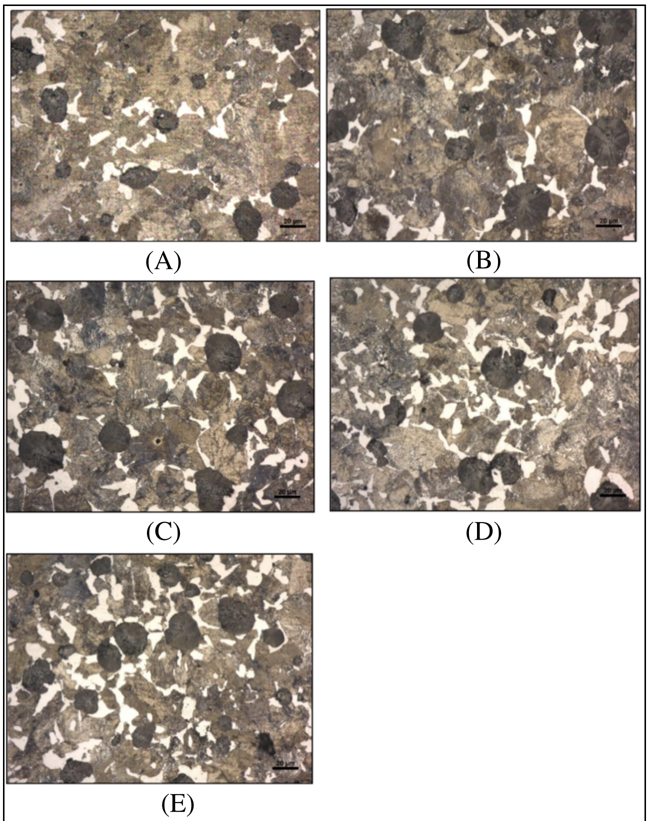

Figure 9. Micrographs with etching: A) as cast; B) 1h at 500 ºC; C) 3h at 500 ºC; D) 5h at 500 ºC and E) 7h at 500 ºC.

There was not a significant drop in hardness values on the samples submitted to 500 ºC up to 7 hours. The hardness reduced from 285 HB to 272 HB at surface and from 299 HB to 292 HB at nucleus.

The quantitative metallography is shown in Table 6 and Figure 10 shows the hardness tests results.

Table 6. Microstructure characterization results.

Condition	Pearlite (%)	Nodularity (%)	Surface Hardness (HB)	Nucleus Hardness (HB)
As cast	98	95	285	299
1h / 500ºC	98	95	285	299
3h / 500ºC	95	95	285	292
5h / 500ºC	95	95	279	292
7h / 500ºC	90	95	272	292

The metal matrix and graphite formation showed that there was not significant effect of heating time on the microstructure of the samples.

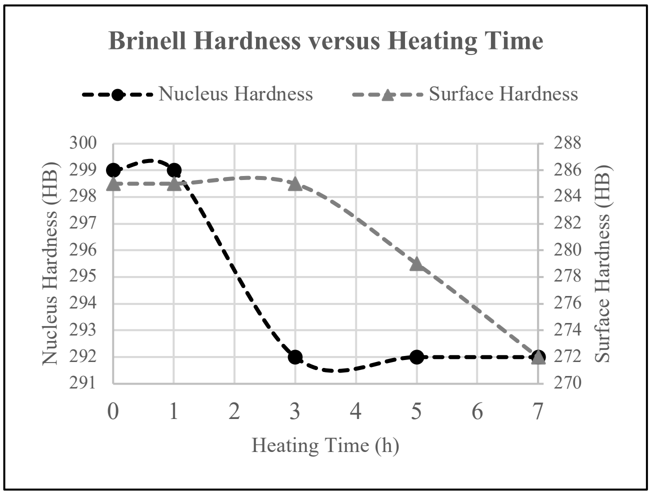

Figure 10. Brinell hardness tests results.

MATERIALS SELECTION – Materials selection is one of the first stages of product development and the right material selection for piston manufacturing guarantees the expected performance for the product.

Although it is a possible material for piston engines production, little information is still available in literature relating nodular cast iron to this type of application. This work presented a data base, and it shall be used to encourage and address new discussion to materials selection for new generation of piston engines. It is expected that studies continue to be carried out to facilitate comparison for designer when deciding which material best suits his needs.

Until now, the most widely used material for piston engines is aluminum. However, the development of new generation of piston engines requires materials with better mechanical properties than aluminum. Although steel is an option for piston manufacturing with higher mechanical strength, this material can be oversized for medium-duty application. In this case, NCI can be an advantageous material to be selected.

The literature relates steel pistons to peak pressures as high as 17,5 MPa and aluminum alloy pistons to 10,2 MPa [9]. For peak pressures between this range, EN-GJS-800-2 alloy can be a technically and economically viable material to piston application.

CONCLUSIONS

Based on the presented results and discussions, the following conclusions could be drawn:

- The material and physical properties characterization of EN-GJS-800-2 alloy at elevated temperatures show that this is a technically viable material to piston application.
- The EN-GJS-800-2 alloy is indicated for medium-duty application, when aluminum doesn't reach the minimum tensile strength required for piston engine and the steel alloy becomes an oversized material.
- Tensile strength at the working range of the engine, that is 400 °C to 500 ºC, is 80% to 62% of the original tensile strength at room temperature, that is 731 MPa at 400 ºC and 556 MPa at 500 ºC. In turn, yield strength is 81% to 75% of the original yield strength at room temperature, that is 432 MPa at 400 ºC and 398 MPa at 500 ºC.
- Fatigue strength limit the survival probability of 90%, calculated through staircase method is 305 MPa at room temperature and 214 MPa at 400 ºC.
- The endurance ratio at room temperature is 0,34 and 0,29 at 400 ºC.
- Thermal conductivity is 25 W/mK at room temperature and 30 W/mK to 31 W/mK between 400 ºC and 600 ºC.
- No significant reduction in pearlite content was found up to 500 ºC after 7h holding time.
- After 7h at 500 ºC, the sample retained 95% of the original hardness at room temperature, changing from 285 HB to 272 HB at surface and from 299 HB to 292 HB at nucleus.

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