VOL. 12, NO. 1, JANUARY 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

MAXIMUM PEAK PRESSURE EVALUATION OF AN AUTOMOTIVE COMMON RAIL DIESEL PISTON ENGINE HEAD

Luca Piancastelli[1] and Stefano Cassani[2]
[1]Department of Industrial Engineering, Alma Mater Studiorum University of Bologna, Viale Risorgimento, Bologna (BO), Italy
[2]MultiProjecta, Via Casola Canina, Imola (BO), Italy
E-Mail: luca.piancastelli@unibo.it

ABSTRACT

This paper introduces a method to linearize a FE (Finite Element) nonlinear problem. This method reduces calculation time by several orders of magnitude. Therefore, head geometry is optimized without supercomputers. In this paper the method is applied to a very critical component: the aluminum alloy piston head of a modern Common Rail Direct Injection Diesel (CRDID) [1-2]. The method consists in the subdivision of the head, in several volumes, that have approximately a uniform temperature. Each volume has an ad-hoc material model that takes into account of temperature, pressure and pressure derivative. Therefore, material behavior depends on average volume temperature, stress magnitude and stress gradient. This assumption is valid since temperatures vary slowly when compared to pressure (stress). In this paper, a known head is analyzed and validated with this method. The head comes from an engine that has run at full load for a known period (60h). It was therefore possible to evaluate true temperatures on head from residual Rockwell B hardness (HRB). This procedure can be considered a reverse engineering approach to evaluate the evaluate the temperature on the engine head. The test was aimed to evaluate the maximum peak pressure possible for the cylinder head. This relatively easy procedure outputted a reasonable maximum value for the engine. In general, experimental tests have confirmed the cost-effectiveness of this approach. This method can be successfully used in many other applications. From the design to the optimization of new or existing critical engine components.

Keywords: optimization, simulation, CAD, geometry, FEA.

INTRODUCTION

Nonlinear FEA of motor head is not all that simple as it might be thought. Indeed, even with most advanced FEA, it is not uncommon that huge discrepancy arises from simulation to experiment. Moreover, a certain growth in loads is commonplace. For instance, in an "old" 8 valves CRDID, the peak pressure design point was around 140 bar. In tests no issues emerged up to 160 bar and the manufacturer will perform tests to reach, at full load, 180 bar. Additionally, true operating temperature is by all accounts out of extent, with design values systematically overcome. This is possible because of the way that the top pressure has brief duration time and the pressure rise is likewise short. The speed (stress rate) couldn't be disregarded in head FEA. Indeed, even with the correct information, simulation takes quite a while. Extremely refined nonlinear investigation ought to be performed with extremely approximated material tables that should include temperature, speed, stress and strain.

Therefore, FEA is more troublesome than expected and long time is required for the investigation with manual refinements into the CAD/FEA model. This procedure is extremely tedious and prompts mistakes. optimization is extremely critical and geometries are adjusted to the numerous boundaries effectively present. At first look, it is relatively easy to distinguish the "design schools" used by the diverse manufacturers. Different geometries take care of the same issues. This reality may imply that the advancement level is not high. Therefore, another methodology is presented in this paper. At initial experimental examination is done to individuate highest temperatures in each point of an existing head. Temperatures are discretized in eight to 16 levels. This procedure individuates volumes with the same temperature level. At that point these volumes of the head with “equivalent” discretized temperature levels are modelled as single 3D parts. Then the head is virtually reassembled to form the original model by utilizing these 3D parts. The FEA investigation is performed by accepting for these parts the congruity of displacements on the normal boundary surfaces. The new load history is given by mono-dimensional (1D) simulation software packages that enables performance and acoustic simulations to be carried out based on virtually any intake, combustion and exhaust system configuration. By giving an ad hoc linear material model (Young Modulus) to every part it possible to perform linear FEA rather than very nonlinear. The Young modulus relies on upon the temperature and on the stress and stress rate slope (as a rule acquired by a 1D Gas flow simulation model of the engine). This linear FE simulation takes seconds even in a commercial Personal Computer. The nonlinear conventional FEA takes hours or days the same computers. In this paper a well-known head of an 8valves, four cylinder CRDID is used as an example. The CAD model of Figure-1 depicts only one of the four heads that are connected together in a mono-block (single mold casting). In fact, the “four” cylinder heads are very similar.

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Table-1. Mechanical and physical properties of the head at 20 deg C.

Hardness	125	HB
Ultimate tensile stress	295	MPa
Yeld tensile stress	245	MPa
Young Modulus	81.35	MPa
Specific Thermal Capacity	0.962	kJ/kg°C
Density	0.0157	kg/m^3

Cylinder head material

The cylinder head material used in this simulation is shown in Table-1.

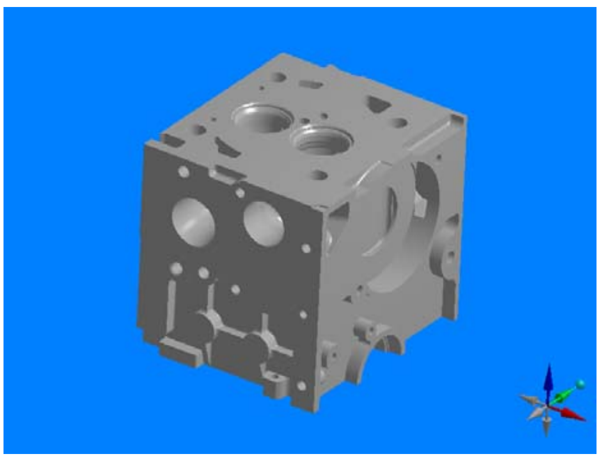

Figure-1. CAD model of the CRDID cylinder head.

Nowadays, most of the automotive cylinder head of modern engines are made of aluminum alloy which, because of its higher thermal conductivity. In fact, aluminum alloy head generally operates about 30–80% cooler than the equivalent cast iron ones. Figure-2 shows the static young modulus versus temperature.

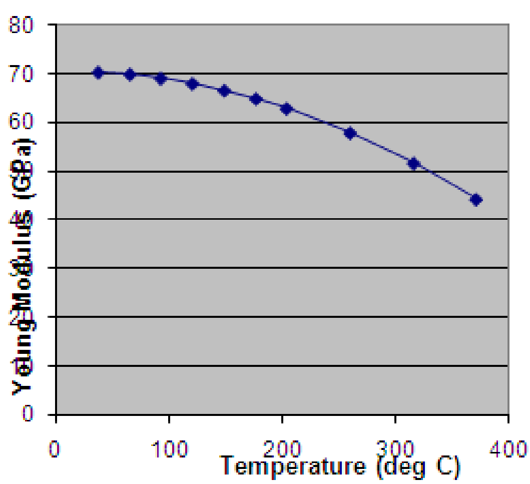

Figure-2. Young modulus vs. temperature (static).

Figure-3 shows the proportional limit versus temperature. As it can be seen the temperature affects drastically the maximum allowable stress.

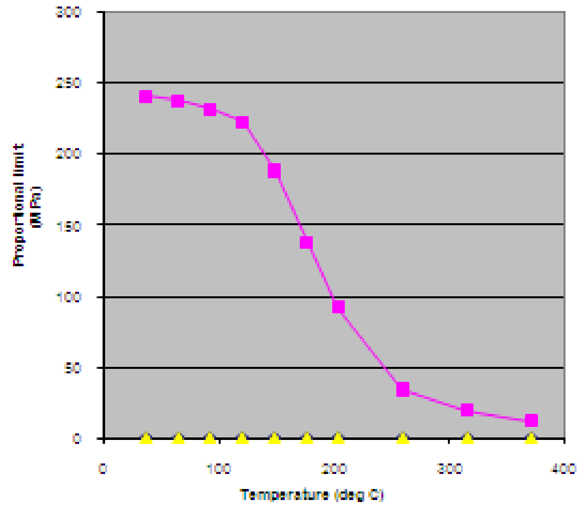

Figure-3. Proportional limit vs. temperature (static).

The main function of the head is to bear to the pressure and seal the pressure of the gases with the gasket. The growth process of pressure inside the cylinder is very fast. The sudden application of a pressure to a body subject to a range of temperatures allows to preserve the values of the higher modulus of elasticity of the lower temperatures due to the inertia. This phenomenon is due the fact that the crystals do not have time to change their properties. In practice the work hardening of the material tends to preserve the mechanical characteristics that normally possesses at lower temperatures.

The hot plastic flow law in function of the deformation given by equation (1).

$$\sigma = K\,(\varepsilon)^n \tag{1}$$

At 20 deg C K=25,200 psi and n=0.304.

The flow plasticity law with temperature may be simplified in equation (2).

$$\sigma = C\,(d\varepsilon/dt)^m \tag{2}$$

Table-2 summarizes the values for C and m of equation 2.

Table-2. C and m for equation (2).

Temperature (°C)	**C** (ksi)	**m**
200	11.6	0.066
400	4.4	0.115
500	2.1	0.211

From Table-2 it is possible to see that m quadruplicates from 200 deg C to 500 degC. Stress and

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deformation rate is therefore fundamental for Young Modulus evaluation at high temperatures. In our example the pressure volume diagram is known from experimental tests (Figure-4) and 1D simulation.

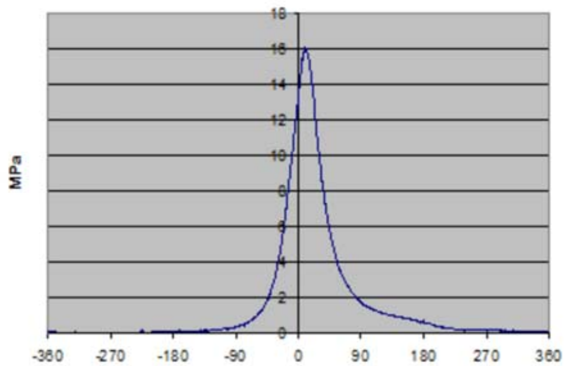

Figure-4. Cranckase degree vs. pressure (MPa) diagram.

Since the peak pressure rate is known (Figure-4) and temperatures are also available it is possible to evaluate the "true" Young modulus from equations (1) (2) and Figures (2) (3).

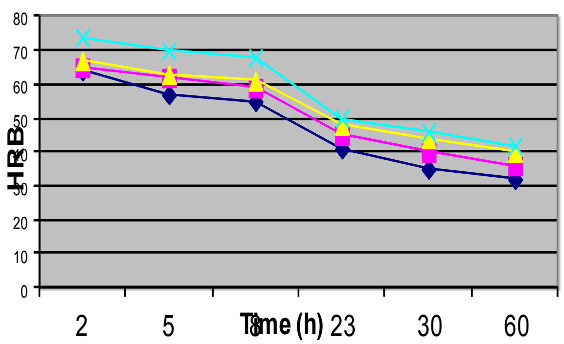

Figure-5. HRB (Rockwell B hardness) vs. time (hours).

Temperature evaluation

Thanks to the experimental tests carried out on the engine it was possible to measure the temperature of the metal of the head detected on the automotive engine in the condition of the maximum power output.

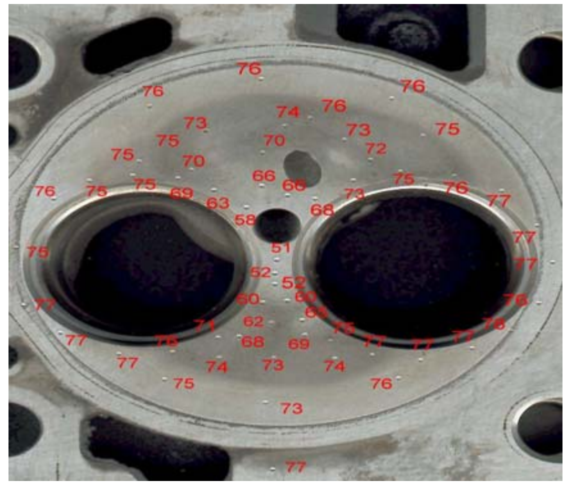

Figure-6. HRB values on the head.

Table-3 shows the values of the intake and exhaust temperatures. These values were detected in an area closes to valve seats.

Table-3. Temperature on head.

	Intake temperature ºC	Exhaust temperature ºC
Cylinder 1	215	235
Cylinder 2	224	247
Cylinder 3	224	242
Cylinder 4	221	239

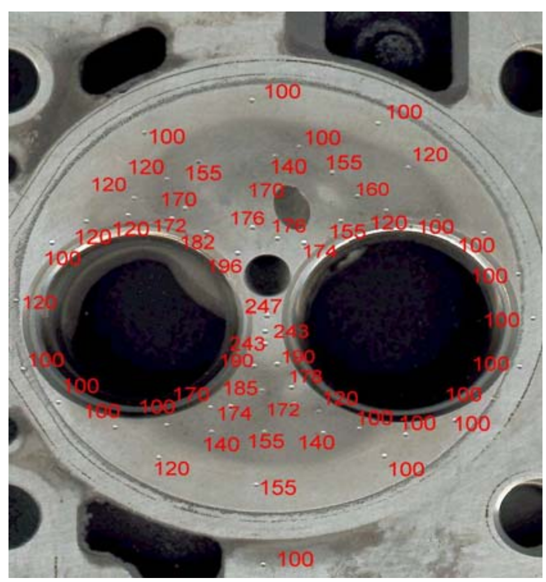

Figure-7. The point measured (numbered from 1 to 100).

The average temperature at the intake is 221 DEG C (point #170 Figure-8) and at the exhaust is 241 DEG C (point #178 Figure-8). These temperatures, however, are

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not sufficient for a detailed mapping of the entire head [3-6]. Not having available the variation of the hardness of the material as a function of temperature, an experimental test was carried out to detect this curve. Several specimens were kept into an oven at different temperatures for different times and the residual hardness was measured. The curves obtained are shown in Figure-5. The specimens have been subjected to temperatures of 180 DEG C (light blue in Figure-5), 200 DEG C (yellow line Figure-5), 224 DEG C (pink line Figure-5) and 247 DEG C (black line Figure-5). The maximum test duration was 60 hours,

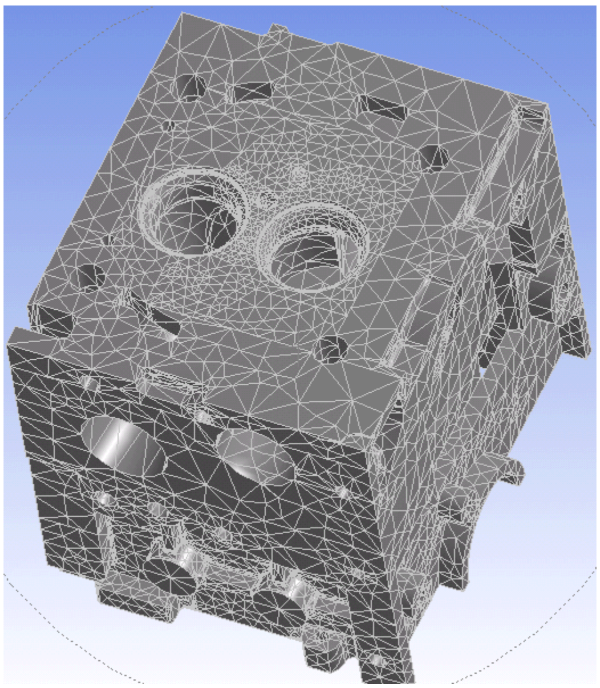

Figure-8. FEA mesh.

that can be considered the time in which our engine run at the maximum power. Then, the residual Rockwell hardness was measured. At this point, the residual hardness on the cylinder head was measured (Figure-6).

Since the temperature of 3 points were known, it was possible to correlate HRB to operating temperature for our head. In fact, the exhaust and intake values were known. The third value is the lower bottom point shown in Figures 6 and 8 (100 deg C). This point is the number 100 in Figure-8. An interpolation was performed to obtain the other operating temperature values. When the engine is not available it is possible to use FE termo-dynamic analysis.

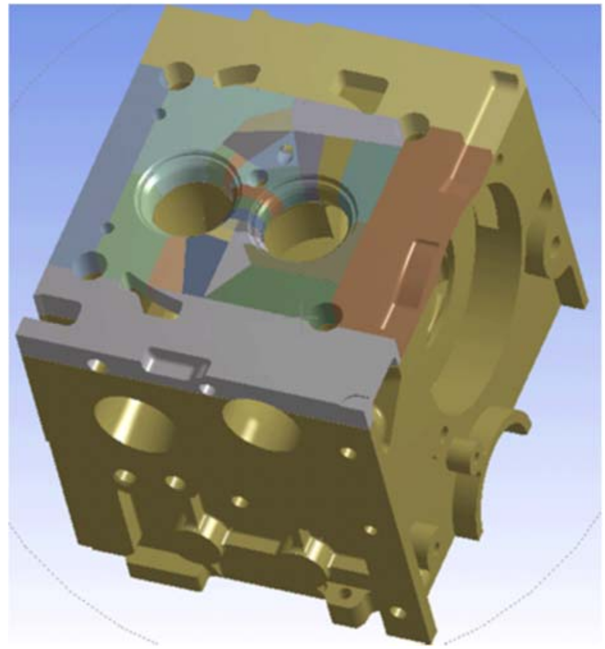

Figure-9. The head assembled with equal temperatures volumes.

Finite Element (FE) model

Finite element model of the cylinder head used in the numerical analysis were generated in order to estimate the stress distribution and structural displacements.

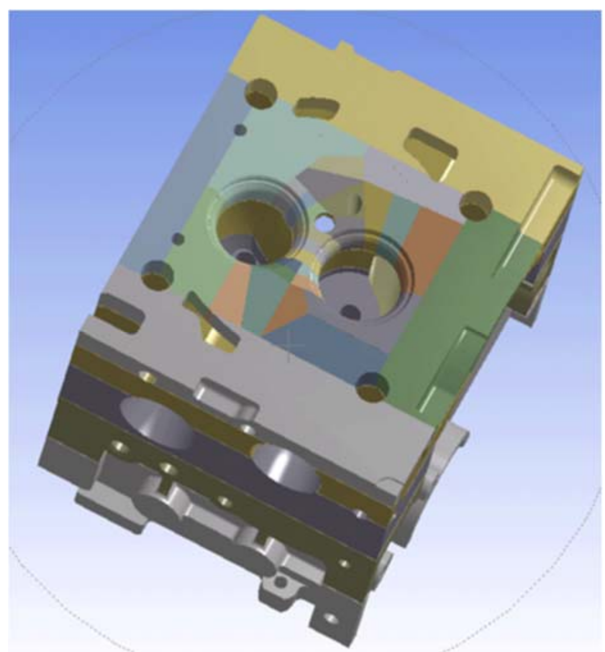

Figure-10. Different view of the CAD model of Figure-9.

FEA also provide results that may be used to evaluate the strength of design based on the von Mises criterion and to identify critical areas. This analysis is aimed to run the engine at the higher peak pressure

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possible. The von Mises stress for a 3-dimensional case can be summarized as the following equation (3):

$$\sigma_{VM} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \qquad (3)$$

The design can be satisfied if the maximum von Mises stress obtained is below the yield strength (proportional limit) of the material. This means a SF=1 (Safety Factor). This SF is typical of automotive cylinder heads. For a good quality of mesh and results, some of the critical areas in the cylinder head were refined.

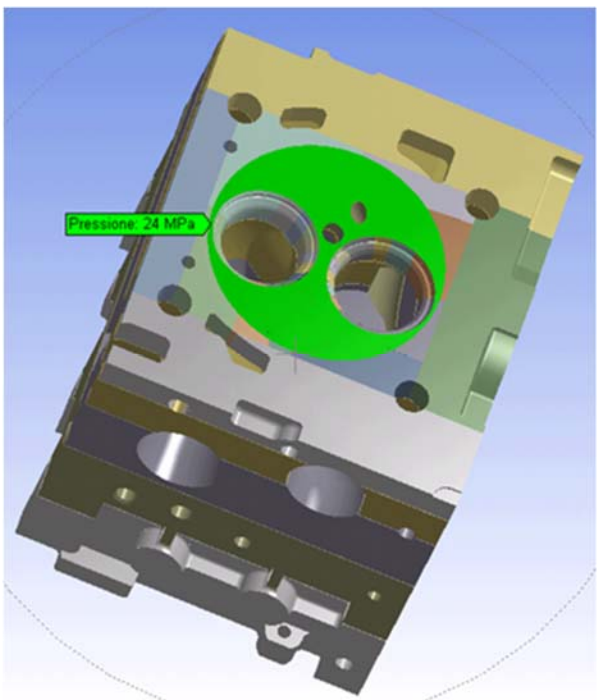

Figure-11. Loads on the FEA model.

The shape around the deck of the combustion chamber that provides the location of the intake and exhaust valves, the injector and the heater plug are the areas of main concern. Therefore, a finer mesh was used in these areas in order to get accurate stress distribution. Hence, a model of the modified cylinder head with 250,000 solid elements and 400,000 nodes was produced, as shown in Figure-8. This mesh was obtained on the assembled head. In fact, the cylinder head has been divided into areas with "uniform" hardness and then these areas were given the corresponding temperature calculated from the hardness/temperature tests. This was possible since the temperature of the coolant in the critical areas of the head is approximately known. Therefore, a FE thermal analysis makes it possible to calculate the temperatures of every point of the cylinder head. It is then possible to define the different volumes for the FEA.

Figures 8 and 9 show the cylinder head divided into several distinct volumes by different colors. Each volume has a defined temperature. To each temperature value a specific material model is assigned. The load model is a uniform pressure on the cylinder head and another value on the gasket surface. The constraints are positioned under the nuts securing the head (Figure-11). In this way a second FEA analysis should be performed to verify that this nuts don't damage the head. This fact is not uncommon. In this case the temperature distribution is unimportant.

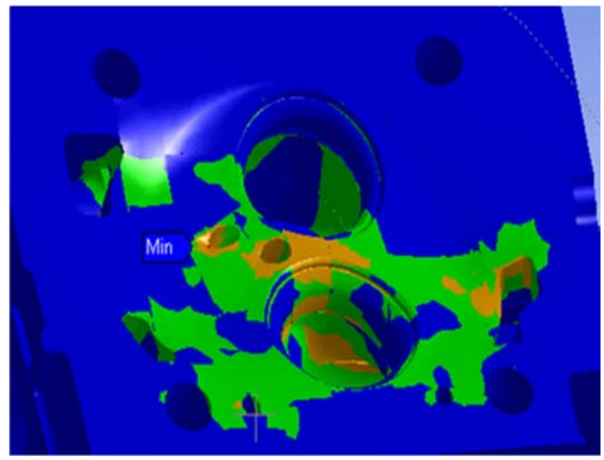

Figure-12. SF (orange SF=1.5), (green SF=5).

RESULTS

The FEA analysis was performed starting from the hypothesis that a variation of the peak pressure does not induce a variation in the maximum temperature values. This is not true. Therefore, the maximum pressure obtained is higher from the simulation is theoretically higher than the maximum pressure truly allowable. However, this linearized method is conservative. This means that, if the temperatures are correct, the FEA underestimates the SF. Therefore, if the power increment is within a "reasonable" value, the value obtained with the simulation is very close to the "true" one. This is always true for existing automotive engines, since components are not over dimensioned for economic reasons. As it can be seen from Figure 12 the SF reaches the maximum value in the "thermal bridge" with a value close to 1.5. This happens for a peak combustion pressure of 180bar. This value can be considered the limit of this head for practical purposes.

The narrow bridge of the deck between the valves and the injectors is almost free of stress raisers on both sides, which is achieved by using generous fillets. Besides, the surface finish in this area should be carefully investigated during the quality assurance procedure to ensure that porosity or sand insertions are minimized. The combustion chamber deck shows the largest displacement under gas pressure load, up to 0.03. Due to the difference in size between the intake and exhaust valves, the distribution of these compressing stresses is slightly different between the inlet and exhaust sides of the cylinder head. The deformations under the gasket seat should also be investigated. The maximum values should be kept within 0.01 mm. This concept is extremely important for engine TBO (Time between Overhaul) [7-9].

CONCLUSIONS

This paper introduces a method to linearize a FE (Finite Element) nonlinear problem. This method reduces calculation time by several orders of magnitude. Therefore, head geometry is optimized without supercomputers. In this paper the method is applied to a very critical component: the aluminum alloy piston head of a modern Common Rail Direct Injection Diesel (CRDID). The method consists in the subdivision of the head, in several volumes, that have approximately a uniform temperature. Each volume has an ad-hoc material model that takes into account of temperature, pressure and pressure derivative. Therefore, material behavior depends on average volume temperature, stress magnitude and stress gradient. This assumption is valid since temperatures vary slowly when compared to pressure (stress). In this paper, a known head is analyzed and validated with this method. The head comes from an engine that has run at full load for a known period (60h). It was therefore possible to evaluate true temperatures on head from residual Rockwell B hardness (HRB). This procedure can be considered a reverse engineering approach to evaluate the evaluate the temperature on the engine head. The test was aimed to evaluate the maximum peak pressure possible for the cylinder head. This relatively easy procedure outputted a reasonable maximum value for the engine. In general, experimental tests have confirmed the cost-effectiveness of this approach. This method can be successfully used in many other applications. From the design to the optimization of new or existing critical engine components [10-13]

Symbols

Symbol	Description	Unit
σ	Stress	psi, MPa
σ_1, σ_2, σ_3	Principal stress	psi, MPa
σ_{VM}	Von Mises stress	psi, MPa
K	Hot flow factor	psi
n	Hot flow coefficient	-
C	Flow plasticity factor	psi
m	Flow plasticity coefficient	-
ε	deformation	-

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