Finite element analysis of thermo-mechanical stresses in diesel engines cylinder heads using a two-layer viscoelasticity model

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Abstract

Loading conditions and complex geometry have led the cylinder heads to become the most challenging parts of diesel engines. One of the most important durability problems in diesel engines is due to the cracks valves bridge area. The purpose of this study is a thermo-mechanical analysis of cylinder heads of diesel engines using a two-layer viscoplasticity model. In this article, mechanical properties of A356.0 alloy, obtained by tensile tests at 25 and 200°C. The results of the thermo-mechanical analysis indicated that the maximum temperature and stress occurred in the valves bridge. The results of the finite element analysis of cylinder heads correspond with the simulation results, carried out by researchers.

***Keywords**: finite element analysis, cylinder heads, Valves Bridge and tensile tests.*

1. Introduction

Cylinder heads are the important parts of the internal combustion engines which are under thermo-mechanical stresses for the sake of their working type [1-10]. Therefore, selection of materials is of paramount importance since they must have sufficient mechanical strength at high temperatures to be able to withstand cyclic stresses caused by heat and pressure [2, 9, 11].

High output capacity, low fuel consumption, low emission and reducing the cost of maintenance are among the restrictions making the design of cylinder heads a complicated task [4, 12]. Thus, detailed analysis and design are essential. Escalation in environmental concerns and fuel costs underlines the need for research on more efficient engines with less energy dissipation and emission [2, 12]. One way to decrease the fuel costs is to reduce the weight of vehicles. Hence, lighter alloys 2 must be used in pursuit of this goal [2, 9]. Recently, the use of aluminum alloys has increased for economic reasons and for improvement of engine power by weight reduction. Aluminum-Silicon is a casting alloy which has extensive use in the automotive industry, especially in cylinder heads of diesel engines. These materials have been replaced by a variety of cast iron which were previously used in the manufacture of cylinder heads [2]. Thermal deformation is the greatest challenge faced by the aluminum cylinder heads [13].

Cylinder heads are exposed to thermal and mechanical loads. The temperature difference, which is the result of turning the engine on and off, begets thermo-mechanical fatigue (TMF) loads on the cylinder heads [2, 4, 12, 14, 15, 16] and consequently reduces their lifetime, especially in thinner regions [17]. The crucial regions include the Valves Bridge and areas near spark plugs and injectors [3, 18, 19]. Cylinder heads endure out-of-phase TMF. Namely, the maximum stress occurs at the minimum temperature and the minimum stress occurs at the maximum temperature. When the engine shuts off and the temperature is low, the tensile stresses arising from assembly loads will be applied to cylinder heads. As the engine starts and temperature increases the compressive stresses produced by thermal loading (σ_{th}) and combustion pressure (σ_p) will be applied to them [2, 4]. This type of loading is displayed in Figure 1. As the figure reveals the changes in stress caused by thermal load is very high. The fluctuating stresses come out of the engine which is been heated and cooled [12, 20, 21].

Plastic deformation is observed in structures like cylinder heads which bear high temperature fluctuations and assembly loads. Classical models are used to obtain steady response of these 3 structures. This approach is very expensive. Because many loading cycles are required to obtain a steady response. Cyclic analysis is used in order to avoid the cost of transient analysis [9].

Numerous papers have been presented on analysis of stress and fatigue in cylinder heads. Koch et al. [22] measured experimentally strain of cylinder heads and compared with simulated results using a nonlinear isotropic/kinematic hardening model. A slight difference between the experimental and simulated strain was observed from 55°C to 120° C. The simulated strain by increasing temperature from 110°C to 210°C was estimated more than the experimental strain due to plastic deformation of the cylinder heads.

Takahashi et al. [13] examined creep in aluminum cylinder heads. There is concordance between experimental and calculated strain. Creep strain increases as stress grows.

TMF of cylinder heads was studied by Thomas et al. [15,16] using the energy model and elasto-viscoplastic law. Their research proved a good agreement between experimental and simulated results of the fatigue life of the cylinder heads and the location of crack initiation.

Thermo-mechanical analysis of cylinder heads and cylinders of AFV diesel engines was conducted by Venkateswaran et al. [23]. Their research demonstrates that the cylinder heads and engine blocks can tolerate more stress caused by pressure and thermal loads.

Su et al. [6] predicted fatigue life of cylinder heads by finite element simulation via the model of damage total and compared with experimental results. Their research revealed that the difference between experimental and simulated results is less than 30%.

Zieher et al. [19] simulated the complete process of lifetime. Their research shows the simulated results of the number of cycles of crack initiation and the location of crack initiation are in accord with experimental results.

The analysis of high/low cycle fatigue of cylinder heads was performed by Ghasemi [24] using the thermo-mechanical analysis results. His study verified that the cracks observed in the experimental test of low-cycle of cylinder heads acknowledged the simulated results of low-cycle fatigue.

Shoja'efard et al. [18] experimentally measured the stress in cylinder heads and compared with simulated results. Their research confirmed the concordance between the experimental and simulated results at low temperature. The simulated stress at temperatures exceeding 200°C was estimated to be greater than the experimental stress by reason of the inelastic material deformation.

Prediction of the fatigue life of cylinder heads of two-stroke linear engines was done by Rahman et al. [25] using finite element analysis (FEA) and stress-life approach. Their research refuted the possibility of failure in all spots.

Gocmez and Pischinger [3] investigated the sophisticated interaction effects of thermal and mechanical loads, geometry of cylinder heads and TMF behavior of cylinder heads material. Geometric dimensions of the valves bridge and thermal conductivity were the most outstanding parameters in the thermo-mechanical analysis of cylinder heads.

Thalmair et al. [7] established the TMF/computer aided engineering (CAE) process for the fatigue assessment of cylinder heads. Their research proved an acceptable agreement between experimental and simulated results of the fatigue life of the cylinder heads.

Mirslim et al. [12] calculated low-cycle fatigue life by simulation of finite element of cylinder heads based on various criteria of strain based. Their experiments show by cutting the valves bridge we can increase the fatigue life of cylinder heads.

Tramprt et al. [8] studied the effects of thermo-mechanical loads on cylinder heads. Their research indicated concordance between experimental and simulated results of the fatigue life of cylinder heads.

Zahedi and Azadi [9] compared the stress and low-cycle fatigue life of aluminum and magnesium cylinder heads of diesel engines. Their research showed that the strain in magnesium cylinder heads was more in comparison with the aluminum ones, while the magnesium cylinder heads had less stress. The fatigue life of the both cylinder heads was almost identical.

Azadi et al. [1] analyzed cracked cylinder heads of gasoline engines. Their research revealed that the main reason for cracks initiation in cylinder heads is high stress and plastic strain caused by assembly loads of cylinder heads bolts.

TMF analysis of gray cast iron cylinder heads was conducted by Li et al. [4] An acceptable agreement between experimental and simulated results of TMF life was proved. Improving and optimizing the structure of cylinder heads doubled their fatigue life.

Xuyang et al. [10] predicted TMF life of diesel engines cylinder heads. Their research revealed that the discrepancy between experimental and simulated results is 3%. The energy criterion accurately predicted fatigue life in the valves bridge compared with thermal shock test .

Metzger et al. [5] predicted the lifetime of cast iron cylinder heads under thermo-mechanical loads and high-cycle fatigue. The mechanical analysis correctly anticipated the position and direction of cracks in the valves bridge.

Aluminum cylinder heads must be adequately robust to tolerate gas pressure, assembly loads and high temperature resulting from ignition to avoid cracking the valves bridge [11]. Thermo-mechanical loading cylinder heads can only be controlled through modern cooling systems or protective coatings such as thermal barrier coating (TBC) that reduces heat stress and thereby reduces the temperature gradient [26].

Azadi et al. [27-30] studied the impact of TBC on cylinder heads. The results of their research demonstrated the TBC reduced the temperature gradient and consequently the thermal stress reduced. Ergo, fatigue life of cylinder heads augmented.

According to the introduction, due of the lack of information on the behavior of hardening, softening and viscosity of materials the analysis of cylinder heads is mostly based on simple models of material behavior like elastic-plastic and the effects of viscosity and creep of cylinder heads are less taken into consideration. Aluminum alloy has creep behavior at about 300°C and viscosity should also be taken into accounted [6, 15, 16, 22]. The main objective of this study was to simulate the thermo-mechanical behavior of cylinder heads based on the two-layer viscoelasticity model. In some analyses, it is assumed that temperature changes have no effect on the stress-strain curves and thermo-mechanical analysis of cylinder heads is non-coupled. Since changes in temperature influence on stress-strain curves, the thermo-mechanical analysis of cylinder heads in this study is coupled. 6

2. Experimental tensile tests

In this study the cast alloy of aluminum-silicon-magnesium has been used to simulate the thermo-mechanical behavior. The alloy is known as A356.0 or AlSi7Mg0.3 which is applied in diesel engines cylinder heads [14, 28, 29, 30]. The chemical composition of the A356.0 is 7.06 wt.% Si, 0.37 wt.% Mg, 0.15 wt.% Fe, 0.01 wt.% Cu, 0.02 wt.% Mn, 0.13 wt.% Ti, and Al remainder [14].

In this article, mechanical properties of A356.0 alloy, obtained by tensile tests based on ASTM E8-E8M standard. Tensile tests were performed under a strain-controlled condition. All tests were conducted using a servo-hydraulic MTS-810 material testing machine (MTS, USA) at 25 and 200°C (Figure 2). The details of tensile test specimens are shown in Figure 3 including the geometry and dimensions.

During tensile tests, the temperature was measured by an infrared pyrometer and a high temperature extensometer was used for measuring the strain. An induction system was applied for heating the specimen.

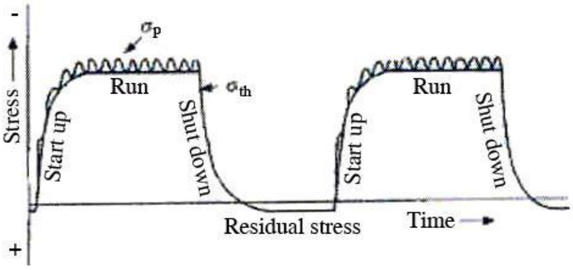

Fig1. The cyclic loading of cylinder head [20].

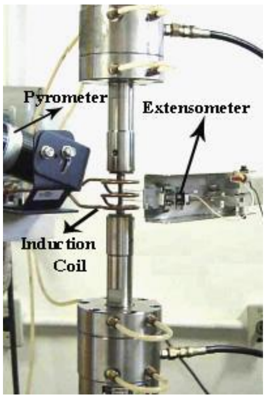

Fig2. Material testing machine MTS 810

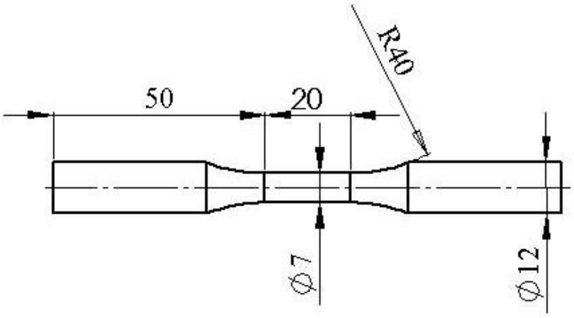

Fig3. The geometry of tensile test specimens and their details (dimensions in mm)

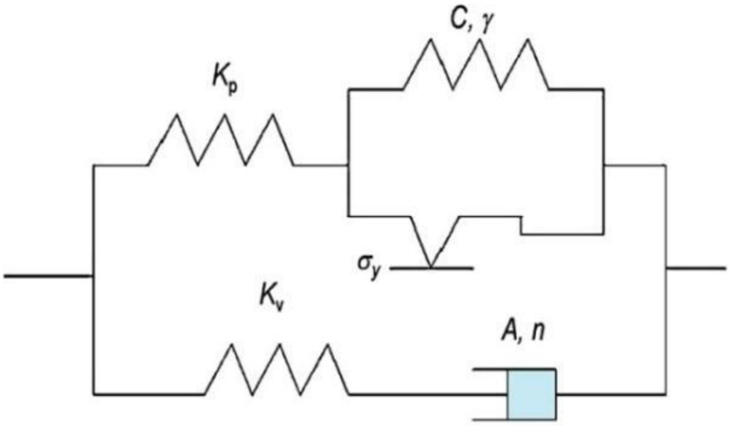

Fig4. The two-layer viscoelasticity model [32].

3. The material behavior model

The two-layer viscoplasticity model divides the elastic and viscosity effects into two elastic-viscous and elastic-plastic networks. As displayed in Figure 4, this model is presented by Kichenin [31]. This model makes the cyclic stress-strain behavior of the material predictable with reasonable accuracy [32].

model consists of a network of elastic-plastic parallel to a network of elastic-viscous. Plastic deformation and creep can be seen in structures such as cylinder heads of engines which are under assembly loads and temperature fluctuations. The two-layer viscoplasticity model is the best to examine the response of materials such as aluminum cylinder heads which have remarkable dependent behavior on temperature and plastic at high temperatures [5, 7, 9, 14, 32]. This model is in good agreement with results of experimental and thermo-mechanical test of A356.0 alloy [14]. The material behavior of different Aluminum-Silicon casting alloys was described by the nonlinear kinematic/isotropic hardening model of Abaqus software [22].

In the plastic network nonlinear kinematic/isotropic hardening model is applied which predicts the behaviors such as hardening, softening, creep and mean stress relaxation and it is a suitable model for the plastic behavior of materials [14, 32].

Kinematic hardening has both linear and nonlinear isotropic/kinematic model. The first model can be used with Mises or Hill yield surface while the second one can only be used with the Mises yield surface and it is the most accurate and comprehensive model to examine some issues with cyclic loading including cylinder heads of engines. The kinematic hardening model assumes that the yield surface, proportional to the value of α, moves as back stress in yield zone but it does not deform [33]. Abaqus software uses ziegler linear model [33] to simulate this model as following equation shows:

$$\alpha = C1\sigma0(\sigma ij-\alpha ij)\varepsilon PL+1CC\alpha ij \qquad (1)$$

Where C is kinematic hardening modulus, $\dot{C}$ is of exchange rate of C in temperature and ε PL is the rate of equivalent plastic strain. In this model σ0 (the size of the yield surface) remains constant. In other words, σ0 is always equal to σ0 (that is yield stress in zero plastic strain) remain constant. Nonlinear isotropic/kinematic hardening model includes motion of yield surface proportional to the value of α in stress zone and also changes in the size of yield surface is proportional to the plastic strain [33]. This model has been extracted from Chaboche experience [34, 35]. In order to introduce this model a nonlinear term is added to equation (1) to indicate the size of yield surface [33].

The Abaqus software uses nonlinear isotropic/kinematic hardening model as following equation shows:

$$\alpha = C1\sigma0(\sigma ij-\alpha ij)\varepsilon\ PL-\gamma ij\ \varepsilon\ PL+1CC\ \alpha ij \qquad (2)$$

Where C and γ are material constants. In order to introduce this model in Abaqus software the isotropic and the kinematics parts are required to be defined separately [14]. In order to define the isotropic part the equation (3) is used in which b and Q∞are material constants [32]:

$$\sigma0=\sigma0+Q\infty(1-\exp(b\varepsilon\ PL)) \qquad (3)$$

The overall back stress is computed from the relation (4) [33]:

$$\alpha= \alpha KNK=1 \qquad (4)$$

In equation (4) if we consider N equal to 3, the hardening variable is divided into three parts which increases the accuracy of the model [14]. 9

Norton-Hoff law is used viscous network in order to consider the effect of strain rate, the equation of which is the following [36]:

$$\varepsilon\ V=A(\sigma V)n \qquad (5)$$

Where the ε V is viscous strain rate, A and n are material constants and σV is the viscous stress.

According to equation (6) the rate of the elastic modules in the two viscous and plastic networks is express by f. Where kv and kp are elastic modules in the elastic-viscous and elastic-plastic networks respectively [32].

$$f=kvkv+kp \qquad (6)$$

4. The finite element model and material properties

Traditionally, optimization of engine components such as cylinder heads was based on building a series of physical prototypes, and performing a series of different experiments and tests. Unfortunately, this method is time consuming and building a prototype in the early stages of the design is arduous. Many samples must be constructed and tested in order to achieve the precise design. This process is costly. These problems have been resolved using finite element analysis to evaluate the effectiveness of various designs. This technique is accepted for the design and development of geometrically complex components such as cylinder heads in a shorter period and with the least cost. Cylinder heads are complex and challenging components of engines, for which the finite element analysis plays a critical role in optimization [18]. TMF analysis of each component needs the cyclic stress-strain distribution. Diesel engines hot components hold complex geometry and loading, and the applying analytical methods for the detection of stress-strain distribution in them are impossible. Many researchers have used finite element method to obtain stress-strain distribution in of geometrically complex components [37]. Nowadays, simulation techniques are substitute to validation tests so as to decrease the cost and time of production [8]. Cylinder heads examined in this study are shown in Figure 5.

Cylinder heads have three valve ports, each with an embedded valve seat; two valve guides; and four bolt holes used to secure the cylinder heads to the engine blocks. Cylinder heads are made of aluminum alloy (A356.0). The two valve guides are made of steel, with a Young's modulus of 106 GPa and a Poisson's ratio of 0.35. The valve guides fit tightly into two of the cylinder heads valve ports and their behavior is presumed elastic. The three valve seats are made of steel, with a Young's modulus of 200 GPa and a Poisson's ratio of 0.3. The valve seats are press-fit into the cylinder head valve ports. This is accomplished by defining radial constraint equations.

The model consists of 65580 nodes and approximately 80000 degrees of freedom. Cylinder heads loading was done in two phases involving thermal analysis and mechanical analysis.

The values of f, n, A and Q∞were extracted from the experimental results of A356.0 from source [14] and they were entered into the Abaqus software.

There are several methods to insert the values of C and γ into Abaqus software that one of them is entering yield stress at plastic strain using tensile test result [38]. The yield stress at plastic strain was extracted from tensile test results and entered into the Abaqus software.

5. Results and Discussion

5-1. Experimental tensile tests results

The stress-strain curves of A356.0 alloy at two temperatures (25 and 200°C) are shown in Figures 6 and 7

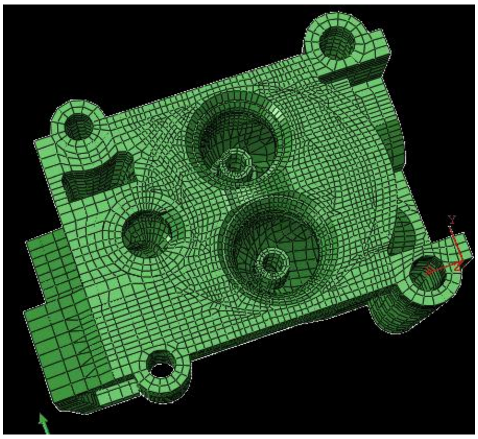

Fig5. The meshed cylinder head [38].

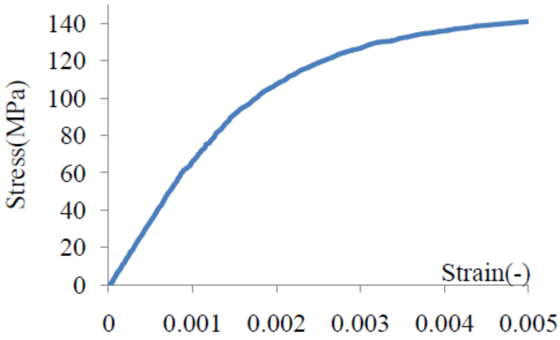

Fig6. Stress-strain behavior in tensile test of A356.0 alloy at 25°C

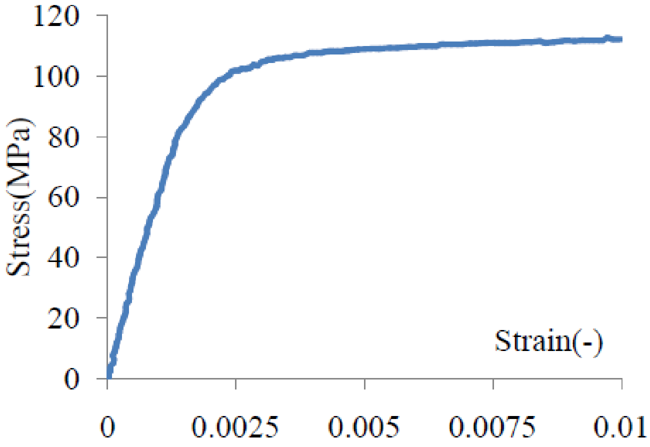

Fig7. Stress-strain behavior in tensile test of A356.0 alloy at 200°C

5.2 Thermal Analysis

Thermal stresses in the cylinder heads are the dominant stresses, leading to low-cycle fatigue in the cylinder heads. Low-cycle fatigue of cylinder heads is caused by repeated start-up and shout-down cycle of the engine [12, 15, 16, 24].The main part of cylinder heads stresses is the result of the thermal loading and the rest is caused by the combustion pressure and mechanical constraints (Figure 1)[12, 18]. Therefore, thermal loading is the most important loading in the thermo-mechanical analysis of cylinder heads.

The more precise the temperature distribution in cylinder heads, the more precise the thermal stresses in different parts of them [12]. Accurate prediction of the temperature of the engine is very crucial and increases the precision of the FEA results [24]. As the accuracy of thermal analysis increases the accuracy of mechanical analysis and fatigue life estimation rises [15, 16]. The combustion pressure causes high-cycle fatigue in cylinder heads [2, 5]. Many researchers believe that the combustion pressure has secondary effect in the TMF of cylinder heads [13, 15, 16]. In finite element simulation the valves bridge, where the greatest thermal concentration exists, is subjected to thermal loading ranging from a minimum of 35°C to a maximum of 300°C [9]. Temperature distribution is shown in Figure 8 when the cylinder heads is heated to the full. Thermal loading has a considerable effect on the fatigue life and the temperature field identifies critical regions [8].

Crack initiation is due to the changes in the temperature field [7]. Plastic deformation and creep are observed under such conditions. The two-layer viscoplasticity model is ideally suited to examining the response of materials in these conditions [5, 9, 14, 32]. In this analysis three thermal cycles are applied to obtain a thermal steady-state cycle. Each cycle consists of two parts: heating the cylinder heads to the maximum operating temperature and cooling it to the minimum operating temperature using the *CFLUX and *FILM options.

The nodal temperatures for the last two steps (one thermal cycle) are assumed to be a steady-state solution and results are saved for mechanical analysis [9]. The maximum temperature occurred in the valves bridge. The lower temperature of the flame and the gradient temperature of the parts of cylinder heads, the less thermal stress. Thus, low-cycle fatigue life of the cylinder heads which is mainly affected by thermal fatigue will increase [21].

5.3 Mechanical analysis

Mechanical analysis was carried out in two stages. In the first stage the three valve seats are press-fit into the corresponding cylinder heads valve ports. Static analysis was used in the procedure. The maximum principal stress distribution is depicted in Figure 9 proving the stress in the valves bridge is tensile.

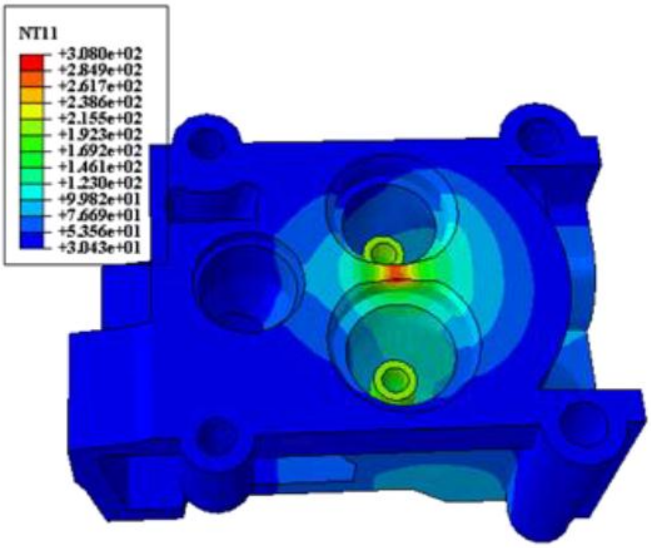

Fig8. The temperature distribution in the cylinder head.

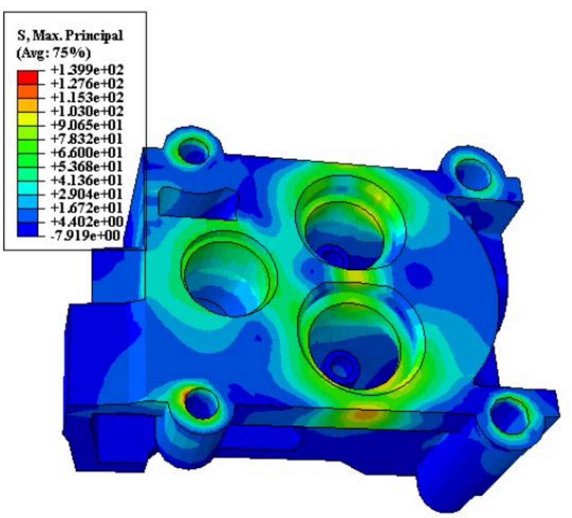

Fig9. The maximum principal stress distribution in the first stage of mechanical loading.

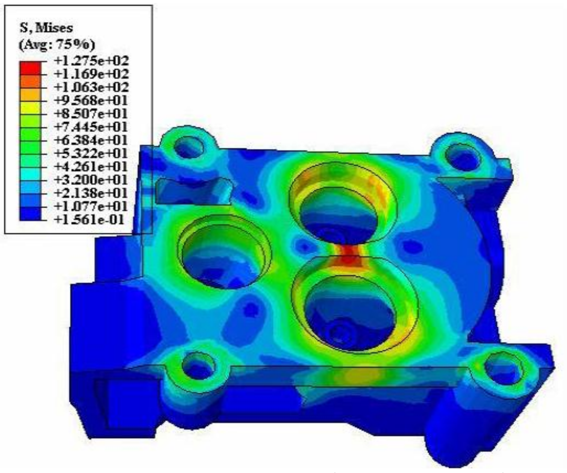

Fig10. The Von-Mises stress distribution at the end of the second stage of mechanical loading.

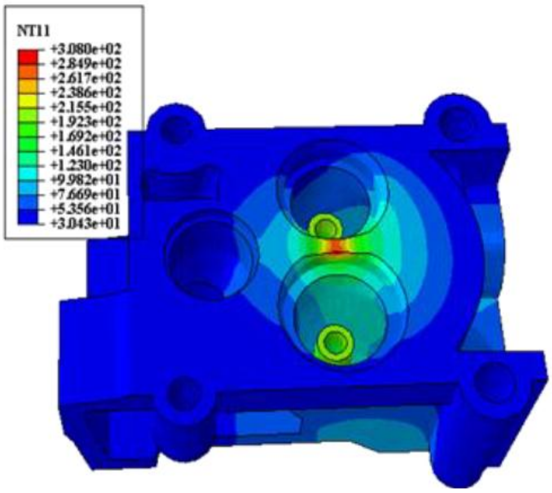

Fig11. The temperature distribution in the cylinder head[39]

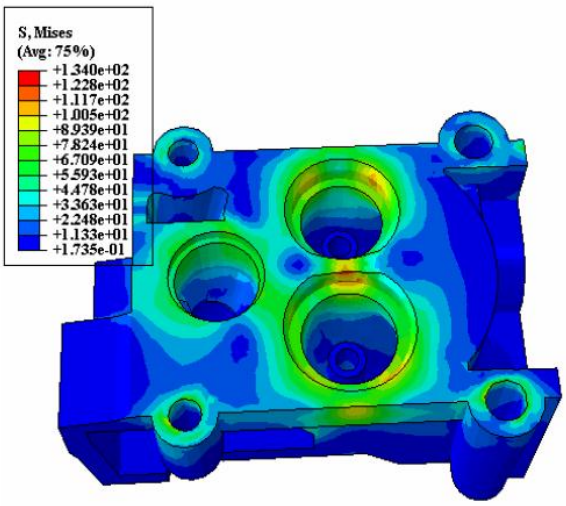

Fig12. The Von-Mises stress distribution at the end of the second stage of mechanical loading[39]

In the second stage the thermal cycle loads were applied so that the material behavior reaches steady state. It is assumed that the cylinder heads are securely fixed to the engine blocks through the four bolt holes, so the nodes around the four bolt holes are secured in all directions [9]. Von-Mises stress distribution at the end of the second stage is shown in Figure 10.

The results of the thermo-mechanical analysis of cylinder head carried out by researchers is shown in Figure 11 and 12. The review of Figures 8 and 10 to 12 reveals there is good agreement between finite element analysis and simulation results of cylinder head, carried out by researchers.

The maximum stress, the same as maximum temperature, occurred in the valves bridge. As stated in sources [4,22] the initiation of fatigue cracks in cylinder heads occurs where stress is tensile for the sake of assembly loads and plastic strain happens because of thermo-mechanical loads. This region is located in the valves bridge. Based on the source [5], the first fatigue cracks can be seen at the hottest spot of cylinder heads (Figure 8). The location of cracks in cylinder heads is in the valves bridge. This region endures maximum stress due to the less thickness of material and high temperature caused by lack of proper cooling. Ergo, the cylinder heads will crack. Stress functions inversely to the thickness of the material. Namely, the thinnest locations withstand the highest stress. If the valves bridge becomes wider, it will be cooled better and consequently temperature gradient and thermal stress will reduce. Thus, fatigue life of cylinder heads increases [3].

6. Conclusion

In this study coupled thermo-mechanical analysis of diesel engines cylinder heads was studied. A two-layer viscoplasticity model was used for this purpose. In this research, elastic and plastic properties of A356.0 alloy, obtained by tensile tests. The results of the thermo-mechanical analysis indicated that the maximum temperature and stress exist in the valves bridge. The results of the FEA revealed there is good agreement between result of thermo-mechanical analysis and simulation results of cylinder heads, carried out by researchers. In order to prevent cylinder heads cracking it is recommended to modify cooling system of engines and thickness and geometry of material in crucial parts. Since the thinner regions endure high stress, cylinder heads crack in these regions. TBC might also be used in the regions which not only boost the engine performance, but also increase the fatigue life of cylinder heads. Since they reduce thermal stress, fatigue life of the cylinder heads grows. Cutting the valves bridge approaches the region to cylinder heads cooling jackets. Consequently, the temperature in the region decreases and fatigue life of the cylinder heads increases.

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