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Fracture Conditions of Piston Rod Beam in Internal Combustion Engine Due to Damage

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Abstract **- In an internal combustion engine, a piston rod joins a piston to the crosshead and thus to the connecting rod that drives the crankshaft. Thus, the most responsible elements in internal combustion engines are the piston, piston rod and crankshaft group. Within this group, the piston rod is an element of great importance given the high loads it is subjected to. In the process of constructing the piston rod, it is important to accurately determine the distribution of stresses and deformations, defining its optimal shape so that no fracture occurs during operation.**

In this paper, the fracture conditions of an internal combustion piston engine due to accidental damage were analyzed. Based on the forces acting on the piston rod, a stress distribution is determined throughout the piston rod. The effect of damage on the piston rod beam on fracture occurrence was analyzed considering the principles of linear elastic fracture mechanics. On the basis of the obtained research results, the impact of the crack length was quantified and recommendations for improving the design of the piston rod were made.

Keywords: Internal combustion engine, Piston rod, Piston rod failure, Crack length, Initiation force.

I. INTRODUCTION

An automotive industry has had a very turbulent expansion and is one of the top industries in terms of development intensity. Production is experiencing a steady increase in industrialized countries. Internal combustion engines are heat engines in which a chemical energy of a fuel is released within a certain working space and converted into a mechanical work in the form of torque on the crankshaft.

Pistons, crankshaft and piston rods are the most important parts of the internal combustion engines. Together with valves, they create a group of so-called moving parts of the engine. Main role of the piston rod is to connect piston with a crankshaft, transferring the force from the piston to the crankshaft, turning linear motion of the piston into circular motion of the crankshaft. The piston rod has to be able to handle great dynamic loads, since the forces that are result of combustion and inertia have very high values. These great dynamic loads can cause fatigue, changing the material stiffness which can lead to fracture of the piston rod. Fractures of the piston rods can occur during engine knocking, pre-ignition, or due to fatigue of the material. When it comes to fractures due to fatigue of the material, the initial fracture crack is usually a micro crack that occurred during forging or some other manufacturing process.

The piston rods for the automotive industry are mainly manufactured by forging from forged steel or powdered metal. They can also be made by casting. The size of the piston rod significantly affects the size of the engine block. It is necessary to achieve as small as possible overall dimensions, as this will result in lower engine mass. Considering the smaller overall dimensions and the task of the piston rod to transfer forces of high maximum values, it is required to be made of high strength material. Therefore, the piston rod is almost exclusively made of high alloy steels for improvement. Based on previous research, fatigue and other factors such as inappropriate material selection, poor design, improperly adjusted screws and mounting are the main causes of piston rod fracture.

Constant pressure during compression phase and tension during expansion phase, over 1000 times per minute, cause fatigue and after a while the material becomes brittle and bursts. Long-term dynamic stresses result in cleavage planes in the material. This is an indication that local plastic deformation has occurred at the center of maximum stresses (the tip of the initial crack in the material). At these points, the material hardens and, upon further periodic loading, an initial microcrack occurs. Very small cracks are a regular occurrence in structures and their parts. Materials science shows that the ever-present microscopic defects, in the form of irregularities in the crystal lattice of metals, result from a number of imperfections in the fabrication process. Fatigue is the growth and fusion of these irregularities, followed by the formation of a crack and its propagation until the final rupture. In most cases, cracks occur at places of greatest stress.

Cracks can be initiated in many ways, such as errors during mechanical fabrication and machining, irregularities in the material etc. It is important to note that they most often

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start to form on a free surface. The microcrack expands until the load-bearing cross section is reduced so that the maximum value of the variable stress can cause instant fracture.

II. MATERIALS AND METHODS

The piston rod is an element of great importance given the high loads it is subjected to. In the process of constructing the piston rod, it is important to accurately determine the distribution of stresses and deformations, defining its optimal shape so that no fracture occurs during operation.

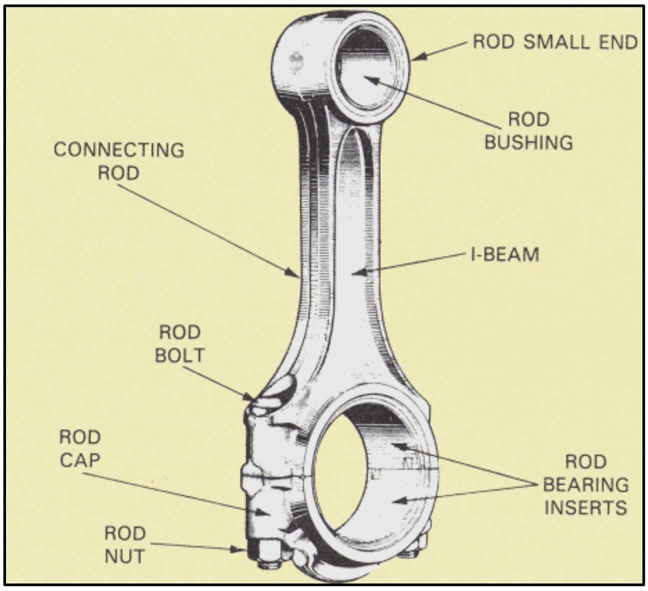

Figure 1: Piston rod parts

Piston rods are made by forging and casting of high-strength materials, since smaller dimensions are necessary in the conditions of transmission of variable forces of high maximum values and high amplitude. They are made almost exclusively of high-alloy steels, mainly chromium molybdenum steel 25CrMo4 ÷ 42CrMo4. After forging and heat treatment, these steels have an ultimate tensile strength of 800 to 1000 MPa, a yield strength of at least 700 MPa and a relative elongation of 12%.

Certain amount of work has been performed earlier on optimization of piston rod shape and weight. For the optimization study, Serag [1] developed approximate mathematical formulas for defining piston rod weight and cost, as objective functions and also constraints. Optimization was achieved using geometric programming technologies. Restrictions are imposed on pressure during compression phase, pressure in rod bearings of small and large end. The cost function was exhibited in an exponential form with geometric parameters. Park [2] investigated the behavior of the microstructure under conditions of different forging and recommends rapid cooling to achieve finer grain size and lower ferrite mesh content. They also optimized the crack separation parameters such as applied hydraulic pressure, angle and parameters adjustment based on delay time, as well as differences in forces leading to cracking. Webster [3] performed a three-dimensional finite element method (FEM) analysis of the piston rod of a very fast diesel engine. The maximum gas pressure value measured experimentally and the maximum tensile stress value, which is essentially the load due to the inertia of the piston mass, were used for the analysis. The stress distribution at the ends of the piston rod was experimentally obtained.

In this paper, the fracture conditions of an internal combustion piston engine due to accidental damage were analyzed. The influence of the crack length on the fracture of the piston rod tree was investigated in order to gain a better understanding of the fracture phenomenon of the piston rod material. In order to achieve greater safety, and avoid the failure of the piston rod, significant thorough investigation of the piston rod material properties under the conditions to which it is exposed is required. FEM analysis of the piston rod was performed and observations related to the numerical results were made. The main assumption used in the analysis is that linear elastic fracture mechanics can provide a reasonable description of the stress field around a crack and therefore the linear elastic fracture mechanics parameter is a good estimate of fracture toughness.

The piston rod of the internal combustion diesel engine was selected to investigate the fracture conditions, with the properties given in Table I. It is manufactured from 25CrMo4 steel, which is high tensile grade of steel that contains chromium and molybdenum, and as a result this grade is often referred to as chromoly steel.

TABLE I
Piston rod engine properties

Effective engine power	118 kW
Maximum revolution	6000 min^{-1}
Engine tact	4
Number of cylinders	4
Degree of compression	9.2
Piston diameter	103 mm
Piston stroke	89 mm
Total stroke volume	3.77 dm^3
Compression volume	0.115 dm^3
Mean effective cycle pressure	0.79 MPa
Maximum cycle pressure	6.48 MPa

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The geometry of the piston rod modelled and used in FEM analysis can be seen in Figure 2. The model is made in SolidWorks software package. The measured mass of the piston rod is 1.27 kg.

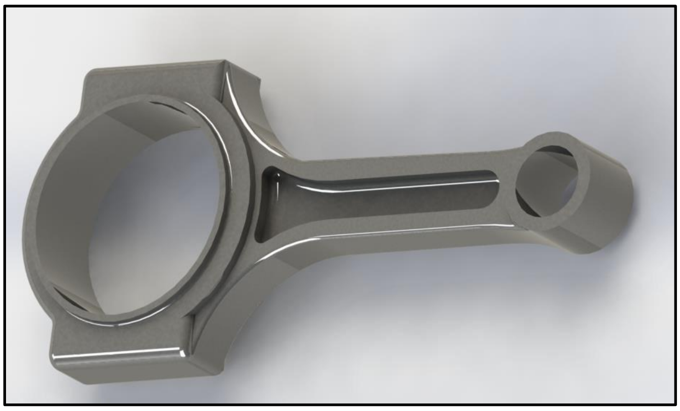

Figure 2: Piston rod modelled in Solid Works

In essence, several types of forces are exerted on the crank mechanism of internal combustion engine:

- Gas force,
- Inertial force,
- Friction force of moving parts and
- Weights of crank mechanism parts.

Friction forces are difficult to determine computationally, so they are expressed through normal forces and friction coefficients in analyses. Friction forces and corresponding moments are, in their intensity, far less than the force of gases and the inertial force. Therefore, considering the stresses on certain parts of crank mechanism, they are uninteresting. The gravity forces on the crank mechanism (weights) are known and are small in intensity compared to the gas and inertial forces. The basic forces analyzed in crank mechanism [4, 5] are therefore the forces from the gas pressure (primary forces) and the inertia forces of the moving parts (secondary forces). These forces experienced in chosen engine model, directed along the piston rod beam, will be used in further investigation.

Gas force externally applied to the crank mechanism *K* is calculated as:

$$K = (p - p_0)\frac{D_k^2 \pi}{4} = f(\alpha)$$

Where p is an absolute value of pressure in combustion chamber above piston, p_0 is a pressure in crankcase (about the same as atmospheric pressure), D_k is piston diameter and α is an instantaneous crankshaft rotation angle.

Since there is no movement of the crank mechanism in the direction of the axis *z*, the main vector of inertial forces F can be written in general as:

$$\vec{F} = X\vec{\imath} + Y\vec{\jmath}$$

The expressions for the inertial forces *X* and *Y* of the crank mechanism take on complicated shapes and depend on the weight of the piston rod, crank pin and crankshaft rotation conditions [6].

Surface roughness or micro-geometric irregularities on the workpiece surface occur during machining of the piston rod. Surface cracks were observed when examining the roughness of the rod beam, and can be seen in Figure 3.

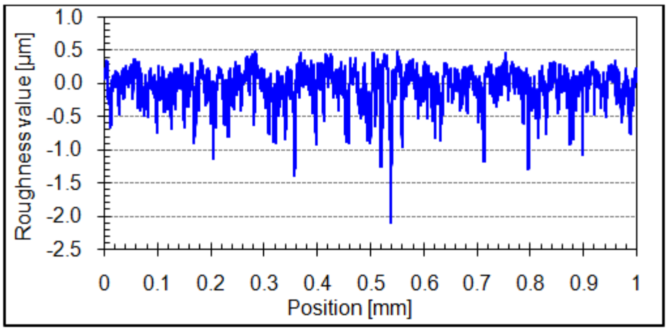

Figure 3: Surface roughness observed on piston rod beam

Due to roughness, cracks with depths of several micrometers occur on the surface of the material. The maximum value of the measured surface roughness on the piston rod tree was 2.12 µm, while the average value amounted to 0.43 µm. This is in line with the work performed by Rakic et al in [7].

III. RESULTS AND DISCUSSION

Influence of the material surface microcracks on the stresses distribution in the piston rod is analyzed in SolidWorks. The impact of microcracks on the piston rod body was examined at depths of 2 µm, 4 µm, 6 µm, 8 µm, 10 µm and 15 µm. The purpose of the analysis is to determine magnitude of force in the piston rod required to cause the fracture in its beam where the microcracks are present.

The result of this analysis showed that the piston rod experiences the highest load when the small end of piston rod is fixed and the large end loaded in compression. This happens during expansion phase when the piston is in an upper dead center. The magnitude of the pressure force taken into account is the maximum value that occurs during the internal combustion engine operation, which for the case of chosen engine was calculated to 140 MPa. The results of the analysis are shown in Figure 4.

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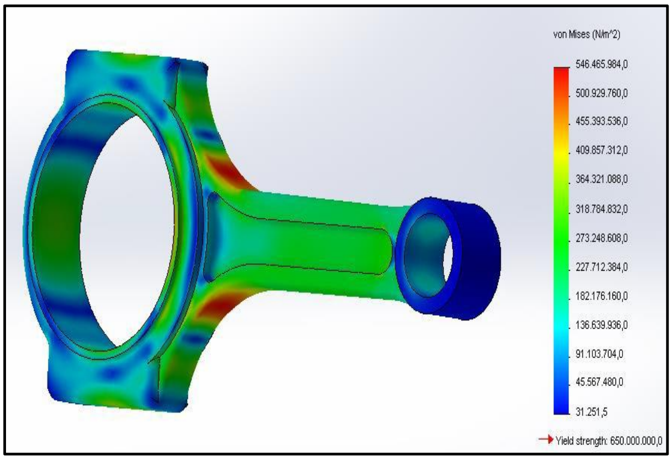

Figure 4: Von Mises stress on piston rod due to compression force of 140 kN

The critical areas, when the piston rod is under compression, are on the part of the beam that turns into a large end. This is also shown by the results of the analysis in Figure 4. Taking this into account, damage to the piston rod body was introduced at the most loaded part, as shown in Figure 5.

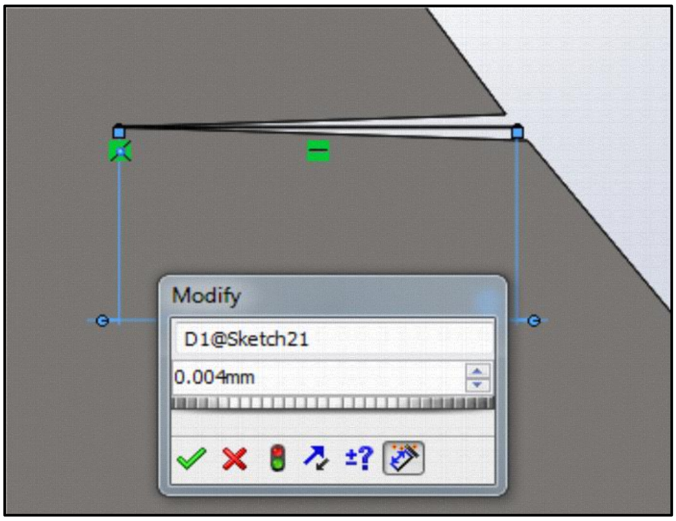

Figure 5: Crack on the piston rod of 4 µm length

A sharp crack was modelled, which represents highly unfavorable case. The larger the radius of the crack tip, the greater force is required to cause fracture. The sharpest crack is the most unfavorable, resulting in higher stress concentration. In such case, the force leading to fracture is much lower compared to the force in case of a blunt crack. Depending on the crack length, the values of forces in the piston rod leading to fracture were examined.

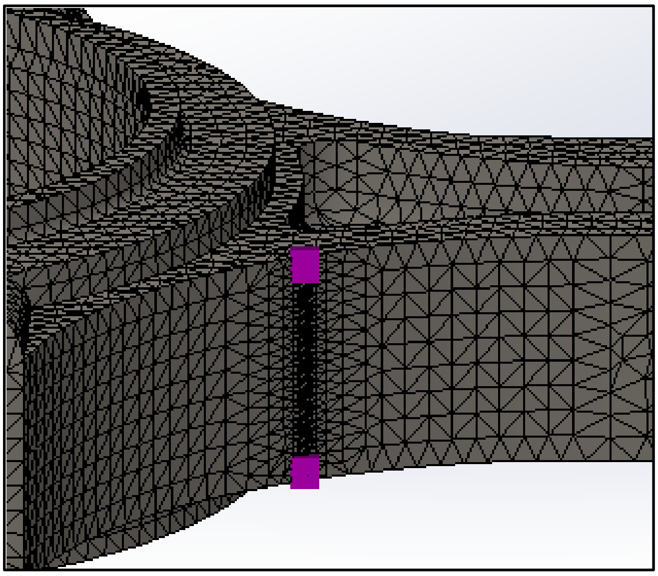

Figure 6: Detail of the mesh around the modelled crack

The finite element mesh was generated using parabolic tetrahedral elements of various size, as shown in Figure 6. Therefore, a finer mesh was adopted for region around the crack where the smallest element size was 0.5 mm. Further from the crack, the size of the elements increases. In other parts of the piston rod, the length of the elements is uniform and is 1.8 mm. Von Mises stress analysis in the immediate vicinity of the crack is shown in Figure 7.

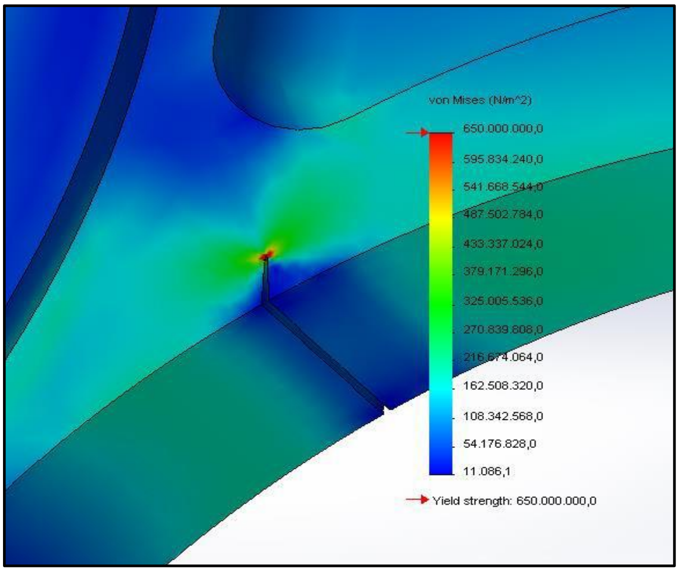

Figure 7: Von Mises stress around the crack tip

After the simulations were performed for different values of the crack length, the magnitudes of forces leading to the piston rod beam fracture were obtained, as shown in Figure 8.

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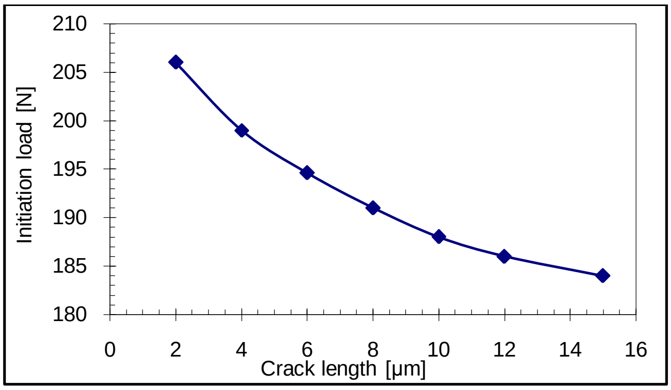

Figure 8: Initiation force required to cause the fracture of piston rod beam as a function of crack length

It can be observed that as the crack length *a* increases, the initiation force F_{in} loading the piston rod required to cause fracture is reduced. Therefore, initiation force is inversely proportional to the function of crack length and their relationship can be written as:

$$F_{in} \approx \frac{1}{f(a)}$$

In order to fracture the piston rod beam containing a crack of very small length of 2 μm, initiation force magnitude of 206 kN is necessary. However, during internal combustion engine operation, force in the piston rod will never reach this magnitude. This leads to the conclusion that the piston rod body will remain undamaged at a given crack length.

Increasing the crack length for a few micrometers will significantly reduce the required magnitude of the force that causes the beam to break. Considering the maximum force magnitude occurring in the chosen engine, it can be concluded that the fracture of the piston rod beam will not take place with cracks of less than 15 μm length.

IV. CONCLUSIONS

The piston rod is exposed to variable loads both in size and direction, due to changes in the operating modes of the internal combustion engine. It is a key element in the operation of the engine and its failure leads to catastrophic consequences.

The condition of the piston rod surface is important to avoid its fracture. However, the outer surfaces of the connecting rod are often damaged. The initial crack is a micro-crack resulting from defects during the manufacture of the piston rod.

In this work, the fracture conditions of the piston rod with a pre-existing micro crack have been considered. Forces that piston rod has to handle (gas force and inertial force) have been defined. The analysis showed that the piston rod body was most loaded by the pressure force on large end at expansion when the piston was in the upper dead center. Modeling of the piston rod with appropriate material properties was performed in Solid Works. Boundary conditions were defined and the FEM analysis of undamaged piston rod was performed. The highest load on the beam, as shown by analysis, is on the part that turns into the large end of the piston rod. This area was chosen to model the crack as the most unfavorable case. Analysis of the influence of the crack length on fracture conditions was then performed. Sharp microcracks with different depths were modelled on the surface of the piston rod. As a result of the FEM analysis, magnitudes of forces that will cause fracture have been determined.

The largest stresses occur at the crack tip, which is the part of the beam where largest roughness is observed. The results show that manufacturing introduced microcracks will not cause beam failure. However, further crack growth significantly reduces the force magnitude required to fracture the piston rod beam. Because of this, testing the surface roughness of the piston rod is highly important in controlling the product after its manufacture in order to prevent the piston rod from failure. Therefore, production of the piston rod by forging instead of casting is recommended, given the advantages of this manufacturing process. It is also advisable to improve the control of the piston rod during serial production, as well as polishing the outer surfaces of the piston rod in the final machining.

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