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Thermal-mechanical coupling analysis of Dump Truck Terex engine piston and investigating the causes of its failure

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Abstract

One of the important and critical pieces of diesel motor is piston which is under simultaneous thermal loading. Obtaining the stress-strain response in these kinds of pieces which are under thermal-mechanical coupling loading is often difficult through laboratory methods. Therefore using of simulation by finite elements software is necessary for determining the stress-strain response in this kind of pieces. In this article, thermal-mechanical analysis of Dump truck Terex engine piston has been done by numerical simulation of finite elements and the causes of failure of empirical sample are investigated. At first, the model of real finite elements of the sample piston is created, then by creating valid boundary conditions and loading, numerical analysis is accomplished. The mechanical properties of piston have been considered according to the accomplished empirical tests. The results indicated that heterogeneous thermal expansion causes to wear the edge of piston's crown. Also two factors of mechanical properties and geometrical conditions are important in determining the factors of piston failure.

Key words: Piston, finite elements, thermal analysis, ABAQUS

1-Introduction

Diesel motor pieces due to the needs related to low weight, high output power and low pollution are under severe thermal-mechanical loads. Piston as one of the main pieces of diesel motor should be designed in a manner that to be able to bear the high heat and pressure resulted from combustion.
Piston is the first movable piece of motor which causes the energy which is released from fuel combustion to become usable. Piston with its movements at first causes to enter the air or air mix and fuel to the cylinder, then it compresses the fuel mix and meantime the compression, it prevents from leakage of gases.
Piston should have necessary firmness and high quality,, moreover it should conduct heat well. The substances which are usually used for constructing the piston are gray cast iron, foundry steel and alloy aluminum. Cast iron or steel are usually used in the structure of heavy motors pistons which don't need much speed and instantaneous acceleration. Failures on piston can be created through three following factors:

- Wear (erosion) during the performance
- Maintenance error
- Failure of cooling and lubrication system

Conduction of heat in piston is very vital because in the event of lack of proper conduction, piston becomes very hot and the danger of sticking it to the cylinder wall by the effect of expansion occurs.

Moreover, for reduction of time, designing cost and doing less tests, proper tools for simulation in analyses should be used. Nowadays, finite elements method is used as a powerful tool in designing. By using of this tool in predicting the temperature and distributing the stress in a piece, its critical regions can be determined and geometrical parameters can be studied and improved. Consequently, obtaining accurate response of stress-strain in piston through simulation of finite element in the stages of designing the motor and also in analysis of its failures is a necessary affair [1].
Distribution of piston temperature gives us the possibility of optimization of thermal aspects of piston with least costs before making the primary sample. The most temperature of each point of piston shouldn't become more than 66% of the melting temperature of related alloy. This temperature range for the alloy of today's motors piston is about 640 Kelvin [2].
Lee has used of finite elements method for analysis of thermal behavior of piston. Due to the symmetry, he has modeled only one-fourth of piston and he has exerted the thermal boundary conditions in symmetric form. For boundary conditions of combustion, he has considered a simple model [3]. Abbas & et al [4] did a three dimensional finite element analysis for describing the thermal-mechanical behavior of diesel motor piston.
Liu & Ritz presented a two dimensional model (axial symmetric) for transient thermal condition in order to predict the temperature of combustion chamber wall.
Vaneli&Yaun by using of finite elements method and three dimensional simultaneous analysis of piston-lubricant-liner have done the thermal simulation of piston. Three dimensional discretization has been done with this hypothesis that lubricant film acts in the form of thermal resistance [6].
Zhiwei& et al in 2007 have investigated the analysis of diesel motor piston yield. In this research, longitudinal and transversal cracks have occurred on piston. The results indicated that primary cracks have been started from the surface of internal hole and they are continued toward out of circle [7].
In a research which has been done by Valdez, analysis of piston has been accomplished by using of finite elements method. In this study, the differences between Aluminum piston and piston which has been made from carbonic substances, in relation with the amount of thermal expansion and their thermal conduction have been investigated [8].

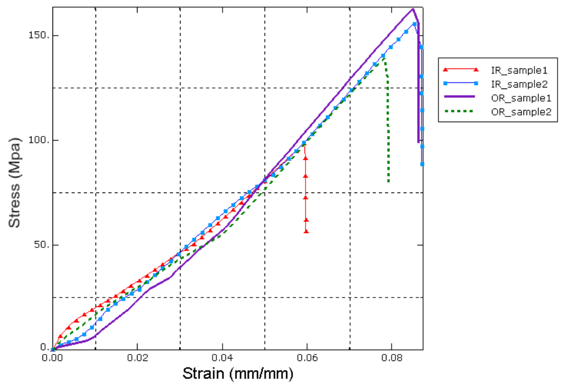
Rampolla& et al in 2013 investigated the analysis of aluminum piston fracture in diesel motor with foundry method according to metalogic system. Assessment of two fractured pistons indicated incomplete combination of atoms and fuel drops which have been melted, have worn the piston body. But the investigations indicated that the important cause of piston fracture is incorrect injection of fuel. This assessment has been accomplished according to visual inspection, metallography, micrographic scan (SEM) and firmness test [9].

The main purpose of the research is to analyze the failure of piston (made in Iran) and compare the original sample with the sample of set of piston which has been made in Iran. Except apparent and dimensional investigation of two samples, investigating the distribution of stress in their finite elements model is accomplished through simulation of round-trip process of piston in ABAQUS software. The results of distribution of stress in addition to the geometry also depend on the mechanical properties of used alloys.

2-Statement of the problem

The main issue in this research is to investigate the causes of failures of piston (made in Iran) and compare it with foreigner sample by numerical simulation of finite elements.

The stress-strain diagram of used alloys in domestic and foreigner samples has been indicated in the shape 1.



Shape 1- the results of tension test in original samples (OR) and the samples made in Iran (IR)

Also investigating and comparing the analysis of genus (kind) and also metallography of Iranian and original samples indicated that much difference hasn't occurred in grade of base aluminum alloy and mechanical properties.

Table1- comparing the results of chemical combination analysis of alloys used in making the foreigner and domestic sample

Element	Sample made in Germany(G)	Sample made in Brazil(B)	First sample made in Iran (R1)	Second sample made in Iran (R2)
Si	11.5	11.2	11.1	11
Fe	0.25	0.5	0.65	0.7
Cu	1.2	1.1	1.2	1.25
Mn	0.06	0.01	0.27	0.28
Mg	1	0.9	0.9	1

Ni	0.85	0.85	0.9	1
Sr	Zero	Zero	Zero	Zero
Al	Base	Base	Base	Base

Also the results of tension and firmness test of samples have been mentioned in the tables 2 and 3. Also the thermal-mechanical properties of aluminum piston have been mentioned in the table 4.

Table 2- comparing the results of tension test of foreigner and domestic samples

Sample	**Tension firmness(MPa)**		**Percentage of relative elongation (%)**	
Made in German(G)	193	193	1	1
Made in Brazil(B)	215	209	1	1
Made in Iran (R1)	170	154	1	1
Made in Iran(R2)	203	207	1	1

Table 3- comparing the results related to measure the firmness of foreigner and domestic samples

Sample	**Firmness (HB)**	
Made in German	95	-
Made in Brazil(B)	73	-
Made in Iran (R1)	85	79
Made in Iran(R2)	92	89

Table 4- thermal-mechanical properties of aluminum piston

S.No.	Name of Property	Value
1	Thermal Conductivity	174.15W.mK
2	Specific Heat	0.13J/kgK
3	Young's Modulus	71e3Mpa
4	Poisson's Ratio	0.33
5	Density	2.77e-6kg/mm^3

Also the sample of failure in internal piston has been indicated in the shape 2.

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Shape 2- severe failure of piston (made in Iran) before deadline

The geometrical model of piston set has been provided with CMM method from real sample. Geometrical investigation of CMM models indicated that there are not the domain slope and the elliptically ratio of cross section of aluminum piston for this sample of piston.

In order to investigate the causes of fracture, thermal analysis must be also done. Thermal stresses in piston lead to low-cycle weariness and also create the mean stresses in high-cycle weariness. Therefore, thermal loading in piston has high importance. Whatever the distribution of temperature in piston is more accurate, thermal stresses which are obtained from it in different points of piston will be more accurate.

Thermal tension in a bounded piece is calculated simply with following relation:

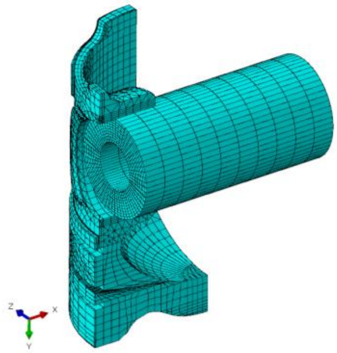
$$\sigma = E\alpha\Delta T \qquad (1)$$

Also, the structural analysis of piston has been accomplished by considering alloplastic properties of substance.

3-Simulation of finite elements

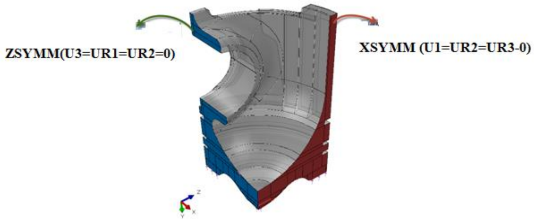
For doing thermal and mechanical analyses, the piston set and its pin have been modeled in three dimensional form. Since geometry and loading in the piston have symmetry, for reduction of time of solving, one-fourth of the piston set model has been used in analyses which has been indicated in the shape 3.

In order to create more accurate results, structured meshwork has been used. C3D6 and C3D10 elements have been used for meshwork of the model. With regard to the complexity of the model, it is necessary that partitioning operation on the surface of the model to be used.



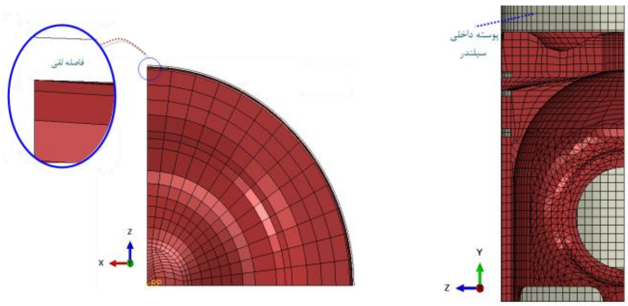
Shape 3- finite elements model of piston set and pin

Boundary conditions have been indicated in the following shape.



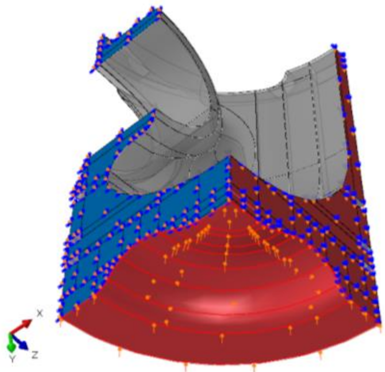
Shape 4- boundary conditions of piston

Also the model of internal wall of cylinder has been in the form of hard crust. Piston with considering the looseness space goes up and down inside this wall and its crown at the beginning of expansion stage is exposed to explosion pressure. The looseness space is usually selected according to the tables of designing the piston.



Shape 5- modeling the internal wall of cylinder in the form of hard crust with observance of the looseness space

The force which is resulted from explosion in the combustion chamber in going stage is imposed to the low surface of piston in the form of hydrostatic pressure. This pressure has been considered with maximum amount of 10Mpa (equal to 100 loads). This step has been designed in a time of simultaneous analysis with going movement of piston inside the cylinder. In other words, in order to simplify, the effects of opposite torque of crankshaft and flywheel and other pistons have been withdrawn and it is assumed the motor is working in stable state.

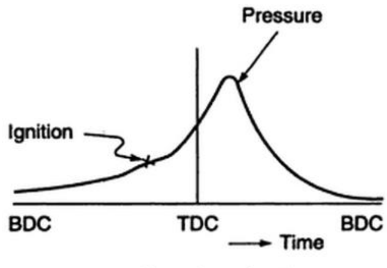


Shape 6- exerting hydrostatic pressure resulted from combustion in piston chamber

According to the measurement of original sample, the space of center to the connecting rod center is 295.75 mm and double of crank arm of 315mm that by using of hard and link models, its mechanism in the finite elements model has been considered.

Thermal loads are some of the complex and important loads of solids problems analysis. Identifying and determining the accurate amount of these loads need to determine the accurate distribution of temperature field in the solid. The temperature of the crown surface is 400° and the temperature of internal surface of cylinder has been considered 150°c.

Thermal-mechanical analysis has been formed of three chronological steps. At first step, the results of distribution of thermal analysis temperature are indicated in the form of stress effects and thermal expansion. Second step is related to the return movement of piston inside the cylinder and third step is done with the addition of hydrostatic pressure of combustion in going stage of piston. With regard to the following shape, in a normal combustion, the peak of pressure is a little after the time of high death point of piston and pressure until reaching to the low death point, reaches to zero in exponential form (shape 7).



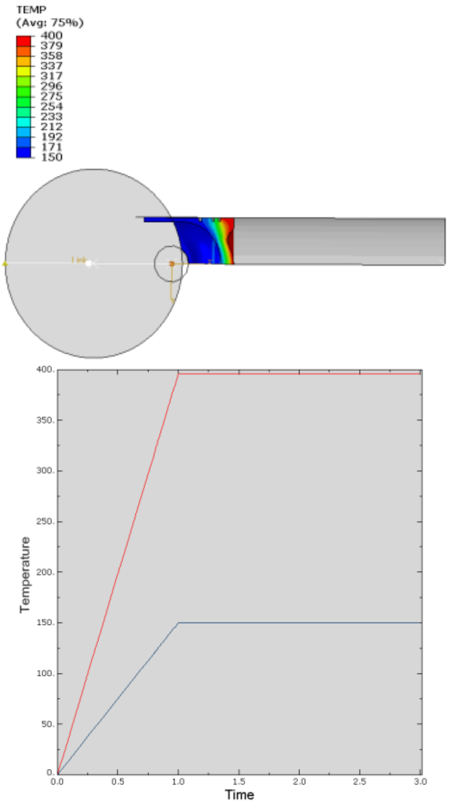
Shape 7- the moment of exerting normal combustion pressure proportional with low and high death points (TDC, BDC)[10]

The amount of peak pressure of combustion diagram of 100 loads has been considered equal to 10MPa which occurs in the third chronological step. The friction coefficient of slippery surfaces of piston and cylinder wall and also the contact surface of pin and piston's hole has been considered 0.2. Pin, cylinder wall and crankshaft have been modeled in hard crust form and the connecting rod has been defined by using of definition of link between pin and crankshaft.

4- Results and discussion

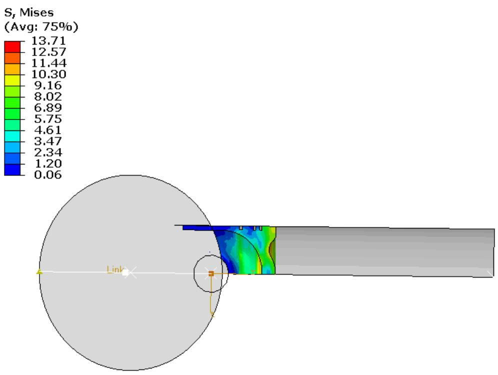
In this part, the results of thermal-mechanical numerical analysis of piston structure are presented.

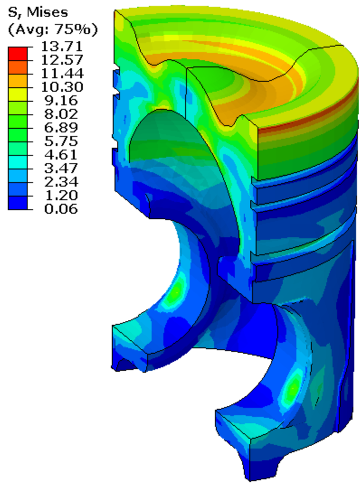
In the shape 8, distribution of fixed temperature in piston since the end of first chronological step to the end of third chronological step has been indicated.



Shape 8- distribution of fixed temperature in piston since the end of first chronological step to the end of third chronological step

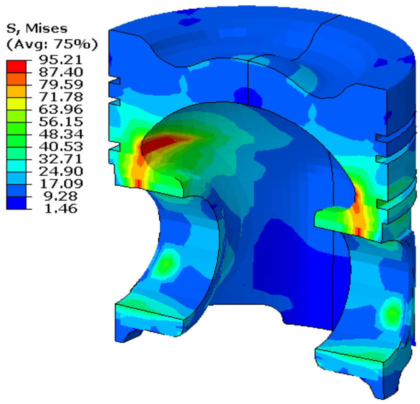
At the end of chronological step of thermal stress analysis, the most amount of stress in the edge of crown is as much as 13.71MPa.



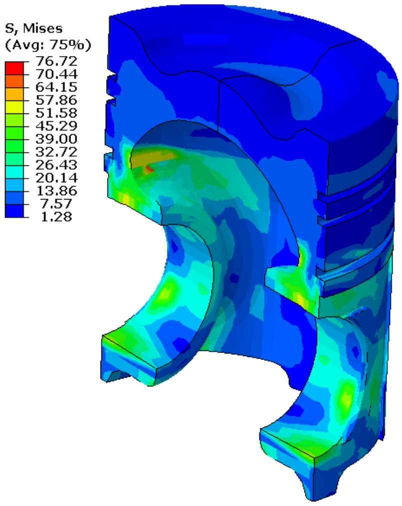


Shape 9- end of first chronological step and distribution of equivalent thermal stress of Von Mises in piston

At the end of second chronological step, the amount of stress in the upper area of pin reaches to 95MPa while in the edge of crown, the stress is 15 MPa. Appearing plastic deformation is probable in a small area around the top of the pin.



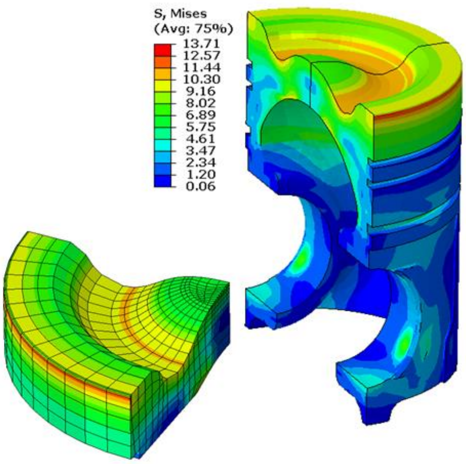
Shape 10- end of second chronological step and distribution of equivalent stress of Von Mises in piston



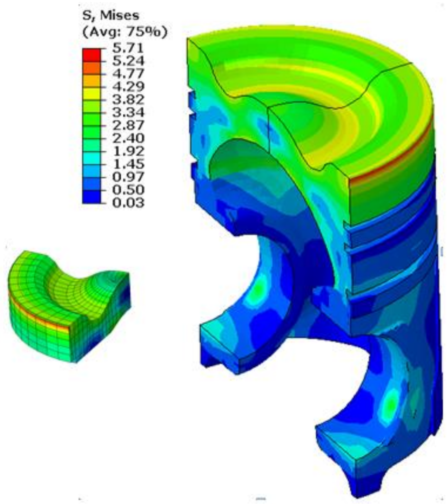
Shape 11- end of third chronological step and distribution of equivalent stress of Von Mises in piston

Investigation of stress distribution history indicated that the amount of stress in the edge of crown doesn't exceed from 15MPa and the most amount of stress occurs with chronological delay of 0.2 since the beginning of going stage of piston.

However simulation of aluminum piston movement inside the solid cylinder with considering specified looseness (0.53mm) has been done for comparing the amount of wear (erosion) one time without considering the expansion effects depending on distribution of temperature and one time with assumption of specified temperature for the crown of piston and distribution of it without considering cooling. All conditions of two samples model are equal and only their plastic properties (stress-strain curve) are different with each other.



(A)



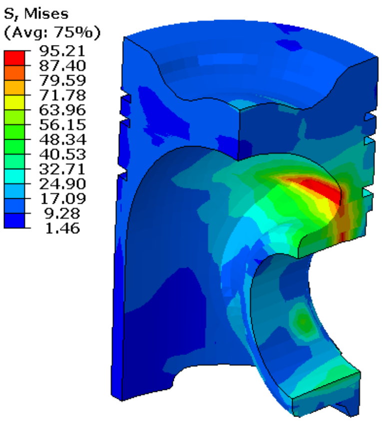
(B)

Shape 12- thermal stress distribution (sytep1) in the piston of samples made in Iran (R1 (A), R2(B))

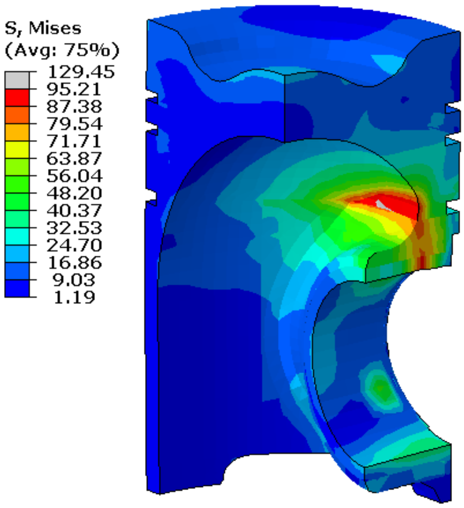
Comparing the distribution of stress created by the effect of gradient degree of heat in two samples made in Iran at the end of chronological step of thermal stress analysis in the above shape indicates that the results of tension test and stress-strain curve have much effect in the created thermal stress. As it is observed, the maximum amount of thermal stress occurs in the crown region and the surface of crown stress in the sample No. (B) that in terms of the tension test results has been similar to the original samples, is less than the half of the surface of the stress distribution in sample No.(A).

Therefore, improper mechanical properties cause to increase the stress surface in the piston surface which increases the failure risk by the effect of wear of the crown edge. Lack of using of proper anti-heat cover in the crown surface, non-observance of proper looseness space, non-observance of the elliptical and conical cross section and weakness in cooling system, each one can intensify this issue.

Investigation of next chronological steps indicated that stress surface is changed in the pin area and it isn't change in the area of the crown edge.



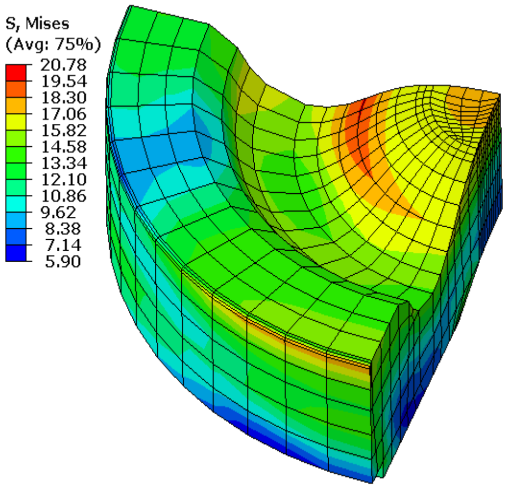
(A)



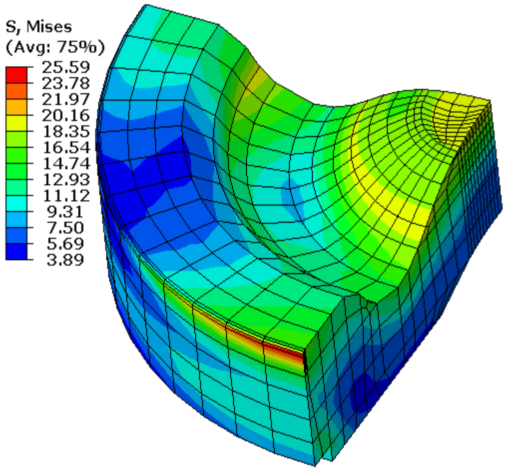
(B)

Shape 13- distribution of stress at the end of compression (step2) in the samples made in Iran (R1(A), R2(B))

With regard to the following shape, the amounts of stress in the crown part aren't very different with each other.



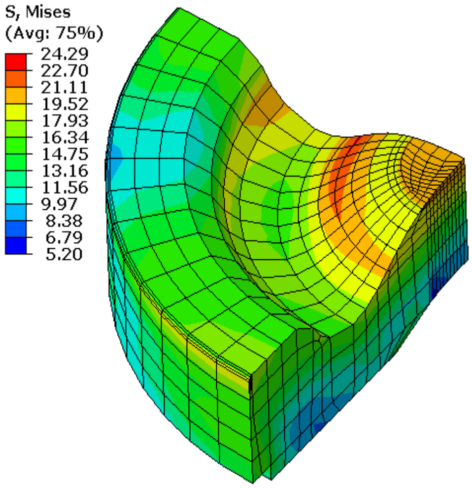
(A)



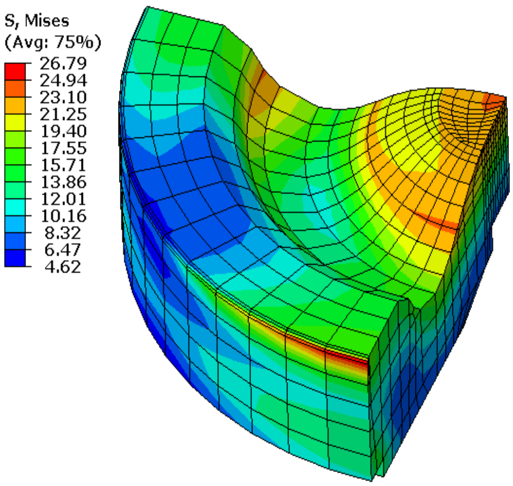
(B)

Shape 14- distribution of crown stress (step2) in the samples made in Iran (R1(A), R2(B))

The maximum stress in the compression and expansion steps of piston occurs in the upper area of pin. In order to investigate the stress surfaces in the crown part, the counter of stress distribution of previous shape in the crown part of piston has been indicated in the following shape.



(A)



(B)

Shape (15)- distribution of crown stress (0.2* step3) in the samples made in Iran (R1(A), R2(B))

Investigation of the analyses results indicated that only in the chronological step (A), maximum stress is imposed on the surface of crown part that tin this state, the stress in the crown of sample No.(A) is more. In the other chronological steps, the maximum stress is concentrated on the surface of pin area that its amount in addition to the substances genus depends on the friction coefficient and also looseness space.

5.Conclusion

In this research, it was indicated that how heterogeneous thermal expansion may lead to the wear (erosion) of the crown edge of piston. The factors of failure of piston can be divided into substances properties and geometrical parts which have been explained in the following:

- Non-observance of the domain slop and elliptical cross section of aluminum piston (geometric factor)

- Non-observance of proper looseness space and deficiency of final machining of the piece (geometric factor)
- Non-observance of the geometry of holes and cooling routes of piston and probable obstruction of them (geometric factor)
- Problem in the combustion or cooling process (system factor)
- Non-observance of alloy and consequently change in the thermal expansion coefficient proportional with reference (substances properties factor)
- Investigation of chemical combination analysis and metallography indicated that the alloy of German sample with regard to the imbalanced silicon percent arising from quick cooling of melted is a post-eutectic kind, but the sample made in Iran is eutectic and as it was mentioned in this research, resistance to the wear of post-eutectic alloys is considerable (substances properties factor).

References

[1] C. Halászi , G. Gaier, H. Dannbauer, “Fatigue life prediction of thermomechanical loaded engine components”. MAGNA Powertrain, Engineering Center Steyr GmbH & Co, Steyrer str. 32, A-4300 St.Valentin, Austria.

[2] Esfahanian. V., Javaheri A., Ghaffarpour. M., “Thermal Analysis of an SI Engine Piston Using Different Combustion Boundary Condition Treatments”, Applied thermal engineering, No. 26, pp. 277-287, 2006.

[3] C.H. Li, “Piston thermal deformation andfriction considerations”, SAE Paper 820086,1982.

[4] M. Tahar Abbas, P. Maspeyrot, A. Bounif., J. Frene, 2004, “A thermomechanical model of direct injection diesel engine piston”, Proceedings of the institution of mechanical engineers Part D: Automotive Engineering, vol. 218, IMechE.

[5] Y. Liu, R.D. Reitz, 1998, “Modeling of heat conduction within chamber walls for multidimensional internal combustion engine simulations”, Int. J. Heat Mass Transfer, Vol.41, pp.859–869.

[6] Wanli. Y., Guohua. CH., Chunfa. W. and Xiaoming. Y., “Simulation of Transient Heat Transfer for Coupling 3-D Moving Component System Within Internal Combustion Chamber”, SAE Paper, No. 01-0617, 2003.

[7] Zhiwei Yu, XiaoleiXu, Hongxin Ding, “Failure analysis of a diesel engine piston-pin”, Engineering Failure Analysis 14 (2007) 110–117

[8] Harigaya. Y., Toda. F., and Suzuki. M., “Local Heat Transfer on a Combustion Chamber Wall of a Spark-Ignition Engine”, SAE Paper, No. 931130, 1993.

[9] B. Rampolla • K. Siegman • J. Spaulding, “Root Cause Analysis of Failed Diesel Engine Aluminum Pistons”, J Fail. Anal. and Preven. (2013) 13:128–135

[10] R.Rudramoorthy, Thermal Engineering, p.211, Tata McGraw-Hill Education, 2003.