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Research Article

Experimental Investigation of Thermal Fatigue life of Engine Cylinder Liner

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Abstract

Thermo mechanical stresses play an important role in the failure of critical parts of many applications like turbines, power plants, hot rolling mills and especially in automotive industry. Thermal fatigue is the major cause of this damage of metals due to thermal cycling. In automotive industry thermal fatigue occurs in engines due to variation in temperature during intake and exhaust stroke. This gradual thermal cycling damage the engine parts especially engine cylinder liner which reduces the service life of an engine. So, it is very important to estimate the thermal fatigue life of engine cylinder liner material. In this research work, thermal fatigue life of engine cylinder liner material grey cast iron has been investigated. A wedge-shaped specimen is prepared from sand casting and used for the experimentation of thermal fatigue. Thermal fatigue experiments are performed between 750C2800C thermal cyclic ranges. Crack initiation and propagation are investigated experimentally on one edge of wedge shape specimen and validate of these propagations of cracks with numerical simulation using ABAQUSTM software.

Keywords: *Thermal fatigue, thermal stress, mechanical stress, crack initiation, crack propagation, crack saturation*

Introduction

The life of any machine part operates at elevated temperatures is usually determined by the properties of its thermal fatigue properties [1]. Thermal fatigue in any part can be induced by fluctuating thermal stresses in it. These thermal stresses are generated when contract part or expand to increase or decrease temperature [2]. The stresses only be generated when internal or external constraints are applied [3]. The fluctuating heating and cooling of the component can generate external constraint due to which forces are produced in it. Due to thermal gradient across the section, an internal constraint is generated. Thermal gradient is generated because heat cannot flow suddenly as compared to the external change and different thermal coefficient of expansion between two phases or grains [4]. Thermal fatigue phenomenon takes place on surface of the material and expands more than internal surface of the material. As internal surface of the material is bulkier, it blocks external layer of surface from expanding. This internal restraint causes compression in internal surface layer.

Heat is conducted from external surface to internal layers, due to which external surface cools down than the internal surface. The compression stresses relieved and tensile stresses induced in the surface. Surface stresses can be determined by the coefficient of thermal expansion and temperature gradient. [5,8]

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These are the images of engine cylinder liner which are damage or cracks are produce due thermo-mechanical fatigue. In engine cracks are produced due to thermal stresses as well as mechanical stresses. Thermal stresses are due to change in temperature and mechanical stresses are due to change in pressure. Problem of material failure is faced due to thermal fatigue in automotive engines, aircraft, steel mills, fertilizer, cement industries, textile industry because materials face high temperature and thermal cyclic loading occurs. Stresses produce in parts due to continuous cyclic thermal loading; components deform and finally the whole system fails. Cast iron and aluminum alloys are used in different power train, automotive components such as cylinder head engine block, cylinder sleeves and piston of engine [9]. cylinder sleeve of light vehicle diesel engine operates on fluctuating temperature and combustion pressure [10].

A failure analysis study of wet liners in maritime diesel engine paper presents a study about failure mechanisms detected in alloyed cast iron liner of marine engine. After 1200 service hours there was appearance of cracks and extensive corrosion, which was located in flange between the liners in the cylinder block. Different techniques include chemical, microstructural, hardness and fractrographic analysis are used to find material characteristics. Composition and microstructure of material was acceptable. [11] Stress and temperature distribution in the critical areas of cylinder liner is presented. Axisymmetric element with reduced integration on 2D finite element code is used and shows that thermal stresses are more serious than mechanical stresses. Two geometries were analyzed which shows that peak stresses were slightly above 100 Mpa in tension. This peak stress value is high for cast iron of liners and results in risk of initiation and propagation of 12 the tiny surface corrosion defects found on cylinder liner at different zones. The second design of liner was better in stress distribution in critical areas, but this was not enough against cracking conditions in the critical areas.[12] A failure analysis study to investigate the cause of cracking occurs in one of the water cooling channels of wet cylinder liner of diesel engine used in warships. Testation of two damaged cylinder liner named as A and B is taken out. The cooling water circulates at high pressure and temperature of water was below 90C at cooling water groove near the top load bearing seating zone of the liner with the cylinder block.[13] During Start and stop of engine, cylinder liner in diesel engine are subjected to low cycle fatigue (LCF).In grooves and assembly notches, these are high stress concentration areas where stress corrosion and corrosion fatigue occurs in wet type designs. The complete failure of liner is not occurred but cracking and corrosion damage was high so that we cannot repair it economically in upper part of liner. All damaged liner were scraped and replaced with new ones [14] Mostly cracking took place in critical zone which is wall circumference therefore engine designers decided to change the local geometry by increasing the radius of curvature of the groove in transition zone with the seating zone of the block from 1.6 to 2.0mm.No other change is introduced in replacement component. By introduction of this change the stress concentration is reduced. After 12000 engine service hours, the cracking starts which is premature time for damage occurrence. Anti-corrosive oil is added to cooling fluid and best results are achieved [15] A competing rick model to describe the reliability of the cylinder liners of a marine diesel engine is proposed. Two dominant modes i.e. wear degradation and thermal cracking of cylinder liners are presented. Stochastic process is used to describe the wear process and weibull distribution is used to describe the failure time due to the thermal cracking.[16] The two models allow performing goodness of fit test and parameters estimation on the basis of both wear and failure data. Reliability estimates of the state of the liners are obtained. For any given age and wear level of the liner, the hierarchy of the failure mechanisms to be determined. The model is applied to a real data set 33 cylinder liners of sulzer RTA 58 engines which have twin ships of the Grimaldi Group. [17] Through using the competing risk model, the estimation of liner reliability and other quantities of interest are obtained and also the conditional failure probability and mean residual lifetime which gives the survival age and the accumulated wear. The model is used to estimate the probability, when both of these modes act that a liner fails due to one of the failure modes[18].

Material and Methodology Casting

Casting is a manufacturing process in which first we melt metal and then poured into a mold. Mold contains a hollow cavity of the desired shape than we solidify the molten metal. Solidification part is also known as casting. We eject or broken out the mould and our process is complete. Metals or various cold setting materials are casting materials are cure after mixing two or more component together, epoxy, concrete, plaster and clay are their example. Casting is used for making complex shapes that are difficult or uneconomical to make by using other methods. We are investigating the thermal fatigue of grey cast iron. Casting technique is used for casting purpose. Large wooden pattern is made for accurate and fine casting. For melting purpose 900C temperature is kept constant for melting of grey cast iron and give extra 10 minutes to prevent solidification at time of poring.

Machining

Casted materials are large in size and different machining process is used for making specimen in accurate size. Milling, drilling, grinding, threading, boring and turning are different machining process. Different machining processes are used to get accurate size of specimen. Actual dimensions are achieved after machining process and when CNC machine is used for machining purpose than close dimensions are achieved.

Material

We used grey cast iron as a testing material. Grade 40 grey cast iron is the material of the liner specified by ASTM but engine manufacturers does not give any material properties. Technical data is as following Continuous power is 3250 KW.

- Peak power is 3600 KW for a maximum of 2 h/day.
- Cylinder bore is 230 mm.
- Cylinder stroke is 280 mm
- 12V cylinder with 11.63 capacity/cylinder with three stage turbocharged.
- Flow rate of cooling water is 30 l/s.

No cracking or significant corrosion is observed at lower part which is a second cooling channel in the lower part. In this region the stresses are low. At room temperature assembling of liner in cylinder block takes place. Sliding fit with manual light pressure belonging to class h6 is an initial tolerance and j5 in the contact zone of the upper part and h6 and for bottom contact zone f5 is used after second cooling channel. The wall thickness of the liner decreases from top to bottom for producing taper shape. [29-31]. This paper describes the results obtained in this failure analysis as

- In damaged areas, the hardness and micro structural analysis of the material.
- In critical zones the stress analysis in the liner.

- The reference temperature used was as 700 ˚C in the axis of piston.
- 250 ˚C in the inner surface of liner.
- 90 ˚C between the liner and block in the water-cooling channel.
- 250 C was maximum service temperature assumed for cast iron. The thermal data used in the analysis is as following. [22, 32, 33]
- Specific heat is 46000 m/˚C.
- Density of the material is 7.25×10^-5N/mm3.
- Thermal conductivity is 34 N/s˚ C.
- Linear coefficient of thermal expansion is 12.1×10^-6/˚C.

Composition of Grey Cast Iron

Grey Cast iron is used in engine cylinder liner because it has a low thermal conductivity and amount of carbon is high. Due to the presence of carbon its colour is grey. Checking the composition of engine cylinder liner on scanning electron microscope and result is shown in Figure 1.1 and Table 1.1.

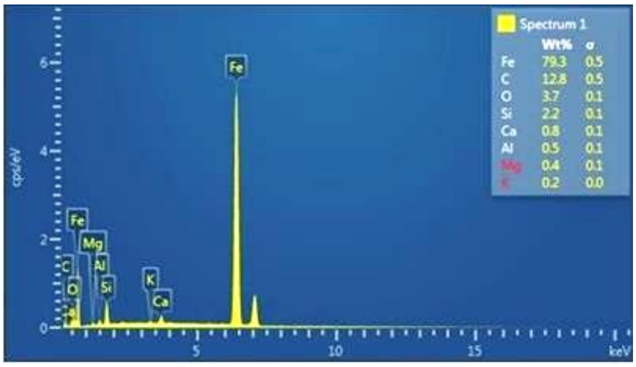


Figure 1.1: Composition of Grey Cast Iron by SEM

There are some issues occurred during testing because scanning electron microscope cannot find the exact composition because of presence of carbon. Spectroscopy is used for finding the true compositions of material and true composition is as following.

Table 1: Composition of Grey Cast Iron by SEM

	C	Si	MN	P	S	Cr	Mo	Ni
I	%	%	%	%	%	%	%	%
	3.84	2.57	0.880	0.175	~0.316	0.125	0.440	0.0336

	Al	Co	Cu	Nb	Ti	V	W	Pb
I	%	%	%	%	%	%	%	%
	0.0074	0.0074	0.189	0.0010	0.0286	0.0104	0.0102	0.00081

	Sn	Sb	B	N	Fe
I	%	%	%	%	%
	0.0035	<0.00040	0.0256	>0.0180	91.3

Surface Preparation for Metallurgy

Surface is prepared before analysis. Scratches, notches and non-uniformity are removed using abrasive grinding paper and then diamond paste is used to get smooth surface. For the purpose of surface preparation following steps are followed.

1- Different grades of abrasive grinding paper are used on material surface. First 400 grade is used then 800, 1200, 1500 and 2000 grades are used to prepare the surface of material.

2- After the removal of scratches

3- Grades of diamond paste is used name as 6R, 3R and 1R. These are applied using Trident cloth.

Results of Microscope

Different magnification lenses are used to investigate the presence of crack, grain boundaries and finding the structure of grey cast iron. Images of different magnifications shown below in Figure 1.2.

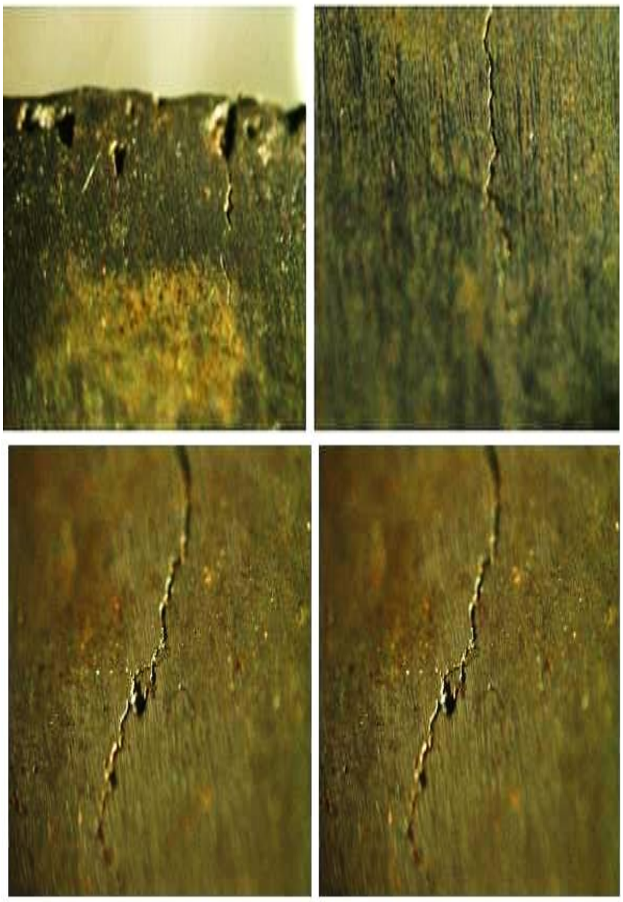


Figure1.2: Microscope Images of Specimen Surface

These images are taken from metallurgical microscope at different magnifications i.e. 50 µm, 100µm.Some cracks appeared on the surface of materials. More details will come from using Scanning Electron Microscope (SEM).

Scanning Electron Microscope (SEM)

Scan Electron Microscope (SEM) is used for testing, scanning and checking the composition of different materials. SEM uses nitrogen gas in his chamber for the creation of vacuum during testing. Testing of grey cast iron is done on SEM on different magnifications. A SEM is a type of electron microscope that produces images of material. Beam of electrons are used for focusing for scanning purpose. The electrons beam interacts with atoms of materials andproducing various signals which contains information about surface of material and composition. SEM resolution is very high and more than 1 nanometer resolution is achieved. Different images got at different magnification which gives the evidence of crack presence and also gives the length of cracks.

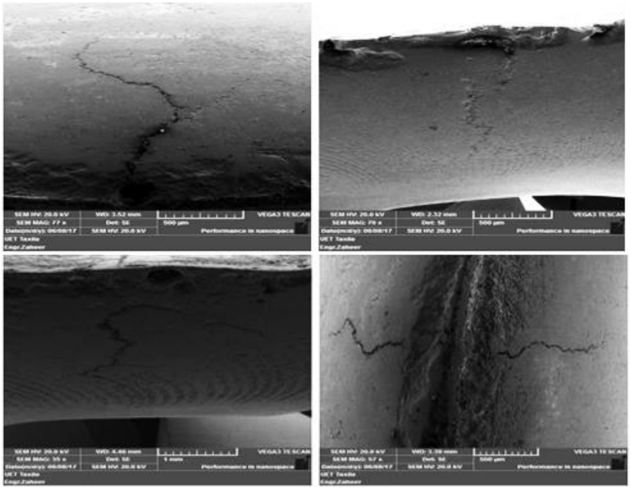


Figure: 1.3 SEM Images of Crack Presence

Figure 1.3 shows cracks of different length are achieved after different cycle of time. First crack produced and then crack propagate and length of cracks increased and finally crack saturated after specified number of cycles.

Result and Discussion

When wedge shape specimen interacts with heating tab then specimen upper surface tries to increase in dimension but water channel in inner side cools its inner part and did not the specimen to expand in heating stroke. In cooling stroke specimen inner side tries to shrink butits tip surface temperature did not allow shrinking and due to these obstacles in compression and expansion of materials thermal stresses are generated in material. Cracks are produced due to continuously heating and cooling and continuously thermal stresses are induced. Our cycle time is 10 second in which 5 seconds for forward movement and 5 second for backward movement. Crack initiated at almost 3000 cycles but due to oxidation film it is not visible. There are three main stages in crack formation i.e. crack ignition, propagation and saturation of crack. Crack initiated at 3000 cycles and continuously propagates at up to 20000 cycle, after 20000 cycle crack propagation stops and crack saturated started.

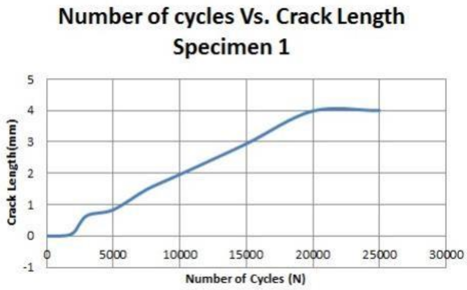


Figure 1.4: Graph between crack length and number of cycles for specimen 1.

In first specimen crack started at 3000 cycles, after 5000 number of cycle the crack length of specimen was 0.836mm and after 10,000 cycles the length of crack was 1.96 mm, after 15000 cycles the length of crack was 2.94 mm, after 20,000 cycles the length of crack was 3.986mm and after 20,000 the crack saturated and length of crack did not increased.

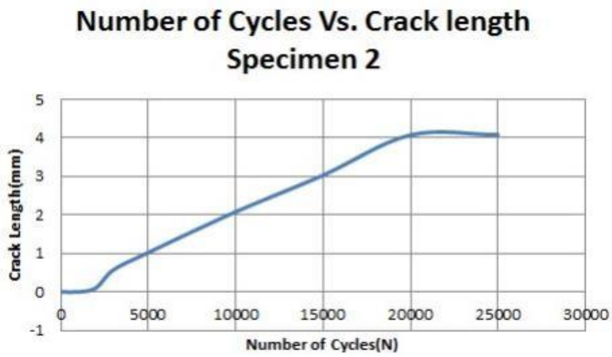


Figure 1.5: Graph between crack length and number of cycles for specimen 2

In second specimen crack started at 3000 cycles, after 5000 number of cycle the crack length of specimen was 1.022mm and after 10,000 cycles the length of crack was 2.08 mm, after 15000 cycles the length of crack was 3.03mm, after 20,000 cycles the length of crack was 4.075mm and after 20,000 the crack saturated and length of crack did not increased.

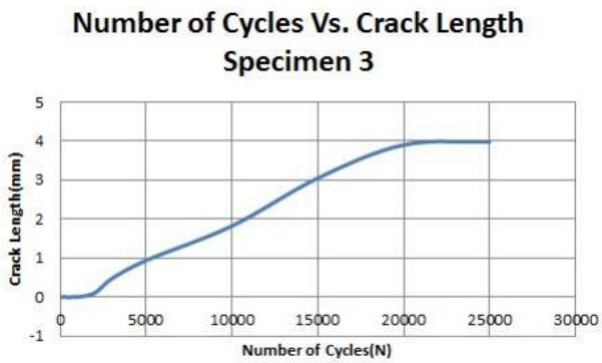


Figure 1.6: Graph between crack length and number of cycles for specimen 3

In third specimen crack started at 3000 cycles, after 5000 number of cycle the crack length of specimen was 0.937mm and after 10,000 cycles the length of crack was 1.821mm, after 15000 cycles the length of crack was 3.05 mm, after 20,000 cycles the length of crack was 3.9mm and after 20,000 the crack saturated and length of crack did not increase.

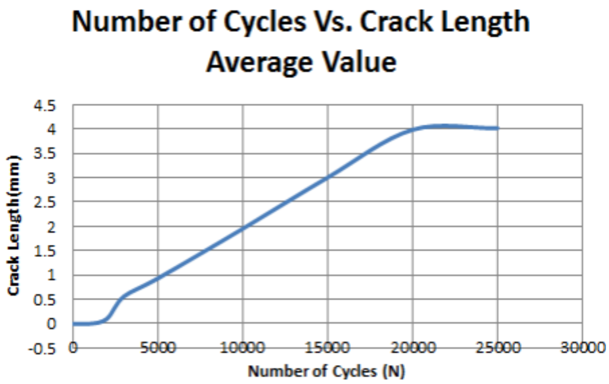
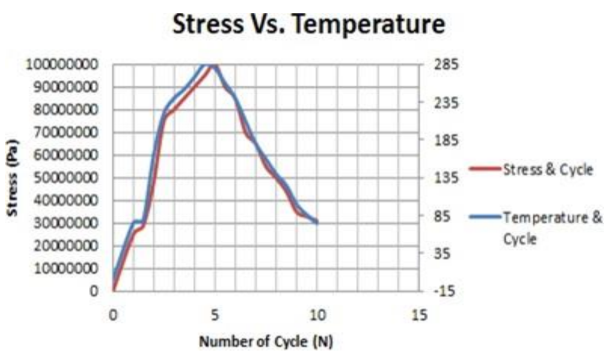


Figure 1.7: Average value between crack length and number of cycles

We took the average value of different crack lengths. In average value crack started at 3000 cycles, after 5000 number of cycle the crack length is 0.931mm and after 10,000 cycles the 58 length of crack is 1.953 mm, after 15000 cycles the length of crack is 3.006mm, after 20,000 cycles the length of crack is 3.987 mm and after 20,000 the crack saturated and length of crack did not increase.

Stress Behavior

As no constrained is applied on specimen therefore there is no mechanical stresses in the model. There are only thermal stresses due to which cracking phenomenon is occurred. Graph is between stress in specimen, temperature along the tip and cycle time. It is clearly shown in Figure 1.7 as temperature of specimen increases the value of thermal stresses also increases.



Energy Release Rate or J-Integral Behavior

Energy release rate is directly proportional to crack length. As crack length increases the value of energy release rate also increases. Analysis of different crack length is done on Abaqus and graph between different crack length and energy release rate is drawn. We did the analysis of different crack length i.e. 0.5mm, 2mm, 4mm and 5mm on Abaqus software. As crack length increases the value of energy release rate also increases up to 4mm but when crack length is 5mm, the value of j-integral decreases that mean crack length can increase up to 4mm.

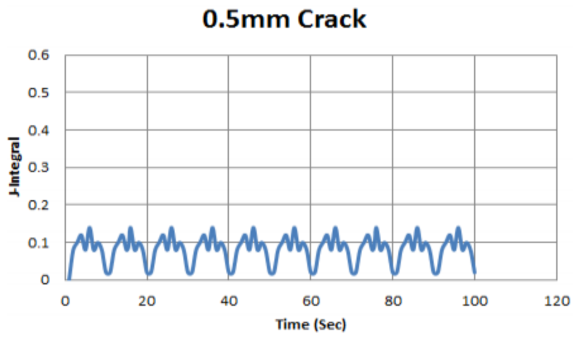


Figure2.1: 0.5mm Crack length

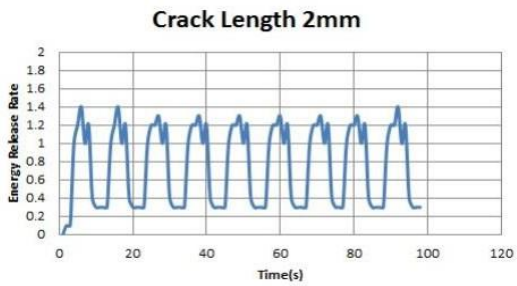


Figure 2.2: 2mm Crack length

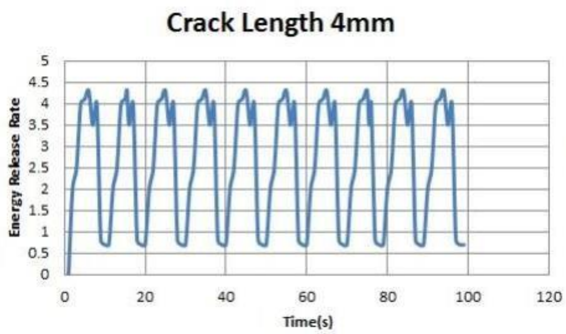


Figure 2.3: 4mm Crack length

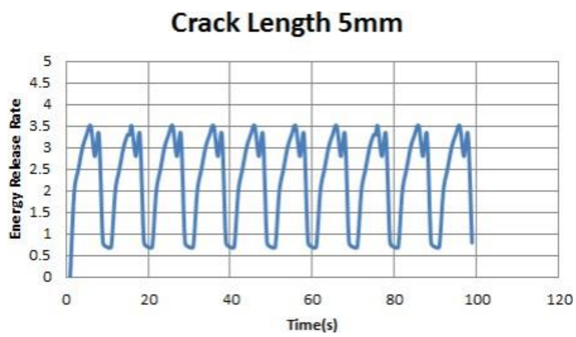


Figure 2.4: 5mm Crack length

Conclusion

In this research work we try to predict the life of engine cylinder liner and for this purpose we made an experimental setup and provide heating at one edge and continuous cooling at other edge to create the thermal gradient. Numerical simulation performed on Abaqus 6.12 software and compares the results of simulation with experimental results.

- Crack initiates at 3000 cycles and propagates up to 4mm at 20000 cycles and after 20000 cycles crack saturates.
- The maximum temperature of specimen during heating stroke is 280 C and 75 C during cooling stroke and temperature gradient is 0 C and the time for heating and cooling is 10 second.
- Materials with low thermal conductivity are more suitable to work on thermal fatigue setup.
- Thermal fatigue life can increase when heating temperature decreases and also by increasing the heating and cooling time.
- The micro structural shows that the cast iron of the liners is homogeneous with stable microstructural.
- Changing in the geometry of the critical zone of the cooling channel of the liner where stress corrosion pitting and cracking observed in service, produce a small improvement in the stress distribution in that zone against the distribution obtained for the original design of the liners. The value of the radial stress in that zone is still high for designs of the liner that can create a great potential for the development of stress corrosion and corrosion fatigue pitting.
- Need for improvement service conditions due to the service environmental and loading parameters being imposed. Replace the cast iron of grade 40 by another type of cast iron with higher tensile strength, namely grades 50 and 60 is a more reliable solution.

Future Recommendations

If someone is interested to work on thermal fatigue or on same thermal experiment setup, then follow these recommendations in future for getting better results and for time saving.

- Water is continuously flowing during cooling and heating stroke. There should be a mechanism to stop water to flow during heating stroke that will increase thermal gradient.
- Use such heating source which can produce maximum temperature i.e. 700ºC, 800 ºC, 900 ºC, 1000 ºC but that source should safe to use. That source should not melt the components of experimental setup.
- Heating and cooling time can be change as per requirement of experiment.
- It is possible to conduct thermal fatigue experiment on different materials but materials with low thermal conductivity are more suitable.

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