การประเมินอายุที่เกิดจากความล้าของท่อความร้อนชนิดสั่นวงรอบที่ติดตั้งวาล์วกันกลับที่สภาวะอุณหภูมิการทำงาน
Fatigue Life Evaluation of a Closed-Loop Oscillating Heat-Pipe with Check Valves (CLOHP/CV) at Operated Temperature

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บทคัดย่อ

การศึกษานี้มีวัตถุประสงค์เพื่อประเมินอายุจากความล้าสำหรับท่อความร้อนชนิดสั่นวงรอบที่ติดตั้งวาล์วกันกลับ โดยกระบวนการทำนายอายุจากความล้าของท่อทองแดงเพื่อนำไปประยุกต์ใช้ในท่อความร้อน CLOHP/CV การทดสอบความล้าจะดำเนินการโดยใช้ตัวอย่างชิ้นงานที่ทำจากท่อทองแดง C1220 ทดสอบที่อุณหภูมิ 293 473 และ 573 องศาเคลวิน รูปทรงชิ้นงานแบบ Hourglass ที่แตกต่างกัน 3 ประเภท แบ่งเป็น Uniform type, One-wave type และ Two-wave type จากการศึกษา พบว่า อายุการใช้งานของชิ้นงานทดสอบจะเป็นผลมาจากการยืดตัวในแนวเส้นตรงของโครงสร้างวัสดุของชิ้นงาน กับรูปทรงชิ้นงาน Hourglass กล่าวได้ว่าจำนวนรอบของความเสียหาย (N_f) จากชิ้นงานประเภท Two-wave รูปทรงชิ้นงานค่อนข้างไวต่อการเคลื่อนตัวของความล้าในระหว่างการทดสอบ โดยที่อุณหภูมิ 573 องศาเคลวิน จะมีผลกระทบต่อความเสียหายมากที่สุด

Abstract

This study evaluates the fatigue life of a closed-loop oscillating heat-pipe with check valves (CLOHP/CV). The method was predicting the fatigue life of the copper tube to apply for the CLOHP/CV. The fatigue test was carried out by using the specimens made of copper tube (C1220) at the temperature of 293 (room temperature), 473 and 573 K. The three types of hourglass shaped specimen included uniform type, one-wave type and two-wave type specimens. It was found that the effect was a direct extension of material structures of specimen and hourglass shaped. It can be said that the number of cycles to failure (N_f) of the two-wave type specimen, hourglass shaped specimen was rather sensitive to fatigue motion during testing, and the temperature of 573 K has the greatest failure impact.

คำสำคัญ : ความล้า ท่อความร้อนชนิดสั่นวงรอบที่ติดตั้งวาล์วกันกลับ รูปทรงนาฬิกาทราย

Keywords : Fatigue, Closed-loop Oscillating Heat-pipe with Check Valves, Hourglass Shape

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1. Introduction

Nowadays, the CLOHP/CV is a new type of heat transfer device. It gives a high performance and several advantages and check valves are installed to the center of heat-pipe to control the flow direction of working fluid so that the flow should be only in one direction (Rittidech et al., 2007), as shown in Figure 1. The CLOHP/CV fabricated by copper tube material. It works well in wide variety of applications, such as cooling in a set of computers by constructing a heat exchanger, etc.

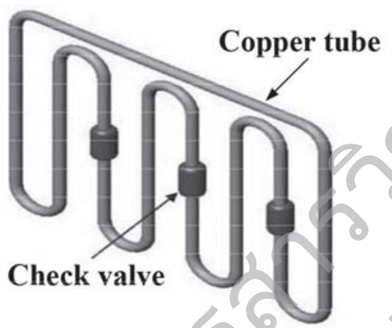


Figure 1 Closed-loop Oscillating Heat-pipe with Check Valve (CLOHP/CV)

But when damage occurs to the CLOHP/CV, its causes being complex and requires time consuming maintenance, so it is imperative to study the fatigue testing in the early design phases of a system to determine the real operating life and projected maintenance requirements before damage occurs. The type of damage relates to the material being used and the avoidance of such damage was determined by performing various tests on the proposed material (Chen et al., 2006). Because the material has been made in a load cycle, it will be damaged under a stress load at a lower yield that varies in the fatigue tests. Sometimes, we have to simulate on a test frequency other than that of the actual usage because of limited time for testing. This can be done if the environment does not affect the frequency of the fatigue damage. In some cases, the temperature being higher than the room temperature or a gaseous environment will affect the frequency of fatigue damage (Miwa et al., 1998). Fatigue was one of the most complicated problems for metal, and the failure mechanism was still not well understood. Expensive test must be conducted to understand the mechanism. If every condition was to be investigated, this result was in many different experiments involving many variables. The problem is compounded by the proliferation of new material requiring evaluation and the increasingly demanding applications for these materials (Sachs, 2005). An ideal situation was designer that should be able to assess, with reasonable confidence, the fatigue response of either a newly developed material or an existing material under conditions for which tests results were not yet available and from a relatively small database of fatigue test results, so as to enable the designer to make preliminary predictions of the probable fatigue lives of the material. Therefore, to obtain more specific data, a copper tube of CLOHP/CV fatigue test specimen was constructed and tested. The copper tube fatigue test specimen was subjected to fatigue load during normal temperature operation and mechanical performance of a copper tube. The test was designed to simulate the hourglass and temperature condition in stressed region of the material and to use system to confirm the basic design concept for further development.

This paper will study the effects of stress to structural geometry on fatigue strength under load-controlled condition at the control temperature, In view of these requirements, an experimental programmed was initiated to examine the fatigue behavior of copper tube (C1220) in the thermal conditions. The fatigue performance of these materials in the thermal condition has been reported earlier. The present work examines the fatigue behavior of copper tube (C1220) in the thermal conditions at 293, 473 and 573 K. It should be pointed out that the effect of the cycle fatigue behavior of these materials was not available in the literature and the present work was the first in this area. All time histories of load and stress as well as photographs of test specimens were recorded and these data were used in conjunction with determination of amplitude, crack initiation and propagation. Several damage accumulation rules were examined with the test data obtained in this study. A damage model considering the effect of non proportionality in loading due to loading mode changes was proposed.

2. Experimental Method

2.1 Specimens and Fatigue Test

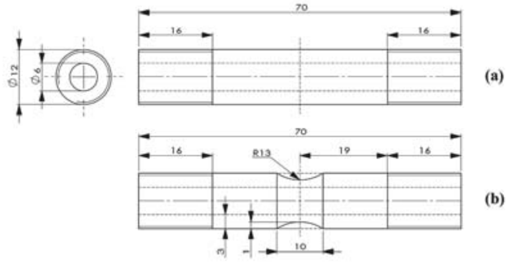
The fatigue test was carried out by using the two models of specimen; labeled as screw-model and flange-model specimens, both of which are made of type copper tube (C1220) as shown in Figure 2 shows the geometry of specimens (a) screw-model specimen (b) flange-model specimen, respectively. By this fatigue test will be applied with CLOHP/CV to determine number of cycles to failure (N_f) and the effect of temperature occurring. By setting the One-wave type was a representative of capillary tube or copper tube and the Two-wave type was a representative of check-valve, which was the area that has changed and the most easily damaged. Because the area was connected to the copper tube and the part of Uniform type that will be used to test for the foundation value of comparison with two shapes of specimens. The surface of specimens was polished mechanically by the #1000 and #2000 fine sand papers. The physical and mechanical properties of testing specimens (in this section refers to the Deoxidized high phosphorus copper (DHP) and C1220) as show in Table 1 were the physical properties and mechanical properties (Shirai & Saeki, 2004).

Comparing the fatigue specimen with cylindrical gage section with an hourglass shaped specimen, the resistance for buckling during push-pull fatigue testing at high strain amplitude was rather high for the latter.

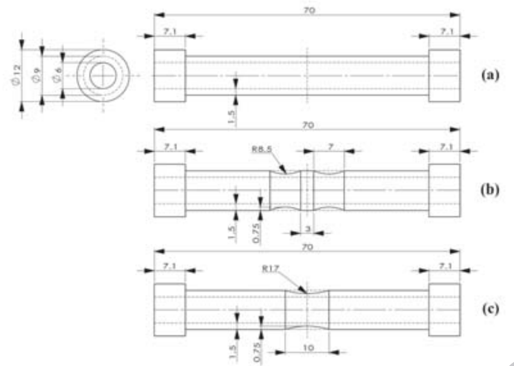
Table 1 Physical and Mechanical Properties

Characteristics	Copper (DHP)	Copper tube (C1220)
Melting point, K	1356	1356
Thermal conductivity, W/(m·K)	339	339
Electrical conductivity, (%IACS)	85	85
Tensile strength, MPa	230-255	260-290
Elongation, %	48-54	20-40

Screw and flange-model were used for the handling and specimen clamping. The configuration of the test area of the specimen was determined to be proportional to the hourglass fatigue specimen with circular cross section in ASTM E2714 (ASTM, 2009). To minimize the effort for the design and the development of the equipment, the material was used in the form of tube which had a tubular geometry with an outer diameter of 12 mm and an inner diameter of 6 mm at the gage section. The bar was cut to the specimen length, total length of 70 mm and the end width of 12 mm were chosen to be same as those for our tensile specimens in current experiments and it has different the hourglass section of test specimen. The configuration of the specimen was shown in Figure 2. This was one of the reasons for the choice of the hourglass type configuration. On the other hand, there were some difficulties in estimating the axial strain range from the results of the diametric strain of hourglass specimens. For this reason, the choice of a specimen configuration with a cylindrical gage section has been recommended by several researches.



Screw-model specimen: (a) Uniform type and (b) One-wave type



Flange-model specimen: (a) Uniform type, (b) Two-wave type and (c) One-wave type

Figure 2 Geometry of Specimens.

2.2 Experimental Setup

The fatigue test was carry out by used of a Shimadzu servo-hydraulic test machine under stress control and a control device (Watanabe et al., 2007), the frequency used in the test was 10 Hz and sampling rate was 200. An electric furnace was controlled by the program, was incorporated in the testing machine for setting the conditions of the test temperature. The operating temperature was taken to be constant were 293, 473 and 573 K, and temperature increasing rate was 373 K/hour. The displacement was measured between two points having this gage length and applied load was measured by the load cell. The data output and input were converted through the AD and DA board from the test machine to the personal computer. Failure cycles applied for specimens were also shown in Table 2. A CCD video camera with a zoom lens was set on electric furnace for monitoring crack initiation and propagation as shown in Figure 3. Laborious procedures associated with optical detection of crack have been reduced by using the automated system of CCD video camera. The present CCD video camera recorded photographs of surface of the specimen every 10 minute with resolution of 1280x1024 pixels.

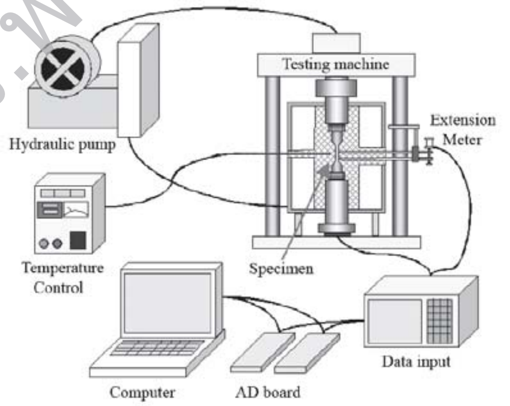


Figure 3 Experimental Setup for Fatigue Test

2.3 Experimental Data

The fatigue loading applied to the specimen was tension-compression. The load was obtained from the load cell of the machine that was converted to stress of specimen, which was obtained by net area of specimens at the center. The obtained strain and stress were regarded as nominal strain and stress, respectively. The obtained axial load was controlled for the fatigue test, and the controlled load changes as alternating cyclic waveform as shown in Figure 4.

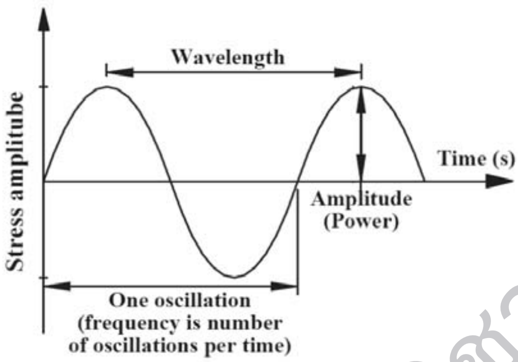


Figure 4 Assumed Load Wave for Fatigue Test

The assumed nominal stress amplitude from peak to peak was 200 MPa for all test specimens which means that maximum tensile stress was 100 MPa and minimum compression stress was -100 MPa, for both types of specimens. Those cyclic loads present load ratio (R) of -1, Shimadzu servo-hydraulic controlled testing machine with 17kN and 7kN load cell was used (screw and flange model, Respectively) and followed concerning specimen by ASTM E2714 which the calculation of the applied load for fatigue test from the shape of specimen base on Uniform type of copper tube which a fully-reversed stress cycle with a sinusoidal form. For this kind of stress cycle, the maximum and minimum stresses were of equal magnitude but opposite sign. Usually tensile stress was considered to be positive and compressive stress negative. Tests were performed with a sinusoidal waveform at zero mean strain for all specimens. Tests were terminated when the specimen was ruptured. Summary of fatigue tests was shown in Table 2.

Table 2 Summary of Fatigue Tests

Model Type	Temperature, K	Specimen Type/Screw or Flange	Failure Cycle (N_f)
Uniform	473	S	47,591
One-wave	473	S	55,854
One-wave	573	S	53,550
Uniform	293	F	307,984
One-wave	293	F	436,757
Two-wave	293	F	203,535
Uniform	473	F	271,131
One-wave	473	F	168,950
Two-wave	473	F	68,791
Uniform	573	F	107,756
One-wave	573	F	13,174
Two-wave	573	F	10,393

The failure cycle number N_f was defined by the number when the tensile load L_{peak} was decreased, and reached 75% of the maximum peak load L_{max}. At this condition, the testing machine stops.

3. Results and Discussion

The summary of experimental failure cycle, the number of cycles to failure (N_f), were shown in Table 2. In this paper, the number of cycles to failure (N_f) was defined as the cycle when the specimen was ruptured and after completing all experiments on the operation of the fatigue, the influences of the various experimental parameters on the number of cycles to failure were considered.

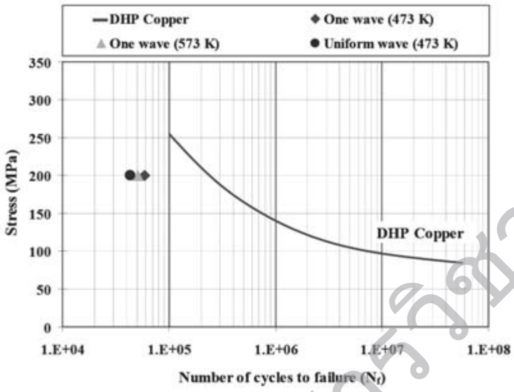


Figure 5 S-N Curves DHP and C1220 in Fatigue Test (Screw-model)

3.1 S-N curves of Copper Tube (C1220) in Fatigue Test

From Figure 5 shows the graph of S-N curve of cupper tube (C1220) which illustrate the stress values and the number of cycles to failure (N_f) values which was known as an S-N curve. A log scale was almost always used for the number of cycles to failure (N_f) then it was found that the stress of 200 MPa, One-wave type specimen values at temperature 473 K was more than One-wave type specimen values at temperature 573 K and Uniform type specimen values at temperature 473 K respectively, which has the number of cycles to failure (N_f) were 55854, 53550 and 47591 and at the temperature 473 K of One-wave type specimen, N_f value was over. Because of the higher temperature, that affects to the molecular structure of copper tube for less taken together so it caused the fracture uncomplicatedly. When copper tube was heated, it would be the one procedure with the metallic material was a linear expansion. By that, the material would be expansion in axis which affected to the thickness of the copper tube, at the higher temperatures, there was more expansion and the Uniform-type at the temperature 473 K was small because the fracture of specimen occurred in screw area at the tip of the screw, not occurred in the center of specimen. Because of this area was fragile by design of tensile-compress load so the fracture would uncomplicated more than the center of specimen which caused the screw-model specimen has the damage problem of this area that it was showed in Figure 7 as show the fracture surfaces obtained of the screw-model specimen at relatively stress levels of 200 MPa of the One-wave type specimen at 573 K and Uniform type specimen at

473 K. Therefore, the researcher would design of the specimens must be improved to the specimen was a flange-model which explains the experiment results of the specimen in Figure 8 and comparing with the graph of DHP copper that found the stress of 200 MP has the number of cycles to failure (N_f) values was approach the DHP annealed copper values. (DHP copper was from material of copper solid material ingots formed parts to fatigue which was the standard value of the fatigue test specimen comparing with copper tube and DHP copper was a literature data (Shirai & Saeki, 2004)).

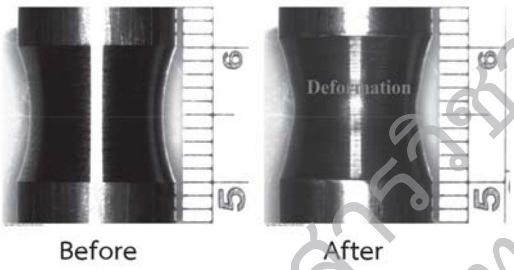


Figure 6 Photographs of the before and after in fatigue test (One-Wave type, 473 K)

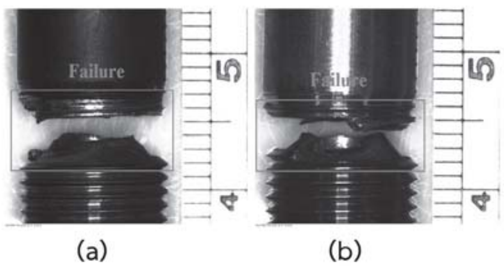


Figure 7 Photographs of (a) One-wave Type 573 K and (b) Uniform-type 473 K in Fatigue Test

From Figure 6 shows the photographs of fatigue test for One-wave type specimen at 473 K in the screw-model, stress levels of 200 MPa in before and after, that can see the after test of the copper tube has deformation.

It was found that the fatigue was a major cause of copper tube specimen because the plastic deformation range will first have undergone elastic deformation, which was reversible, and so that the object will return part away to its original shape. Soft thermoplastics have a rather large plastic deformation range as do copper tube specimen was ductile metals. Under tensile stress plastic deformation was characterized by a strain region and a necking region and finally, fracture (also called rupture). During strain, the material becomes stronger through the movement of atomic dislocations. The necking phase was indicated by a reduction in cross-sectional area of the specimen. Necking begins after the ultimate strength was reached. During necking, the material can no longer withstand the maximum stress and the strain in the specimen rapidly increases. Plastic deformation ends with the fracture of the material.

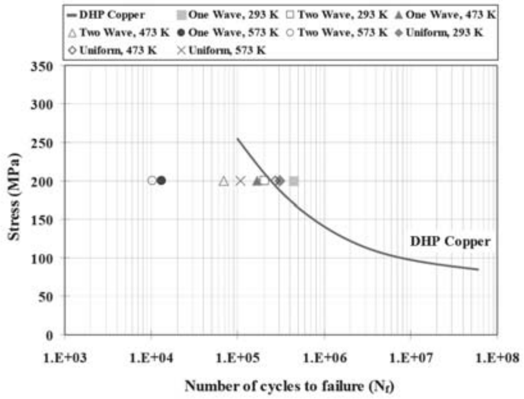


Figure 8 S-N Curves DHP and C1220 in Fatigue Test (flAnge-model)

Another deformation mechanism was metal fatigue, which occurs primarily in ductile metals. It was originally thought that a material deformed only within the elastic range returned completely to its original state once the forces were removed. However, the faults were introduced at the molecular level with each deformation. After many deformations, cracks will begin to appear, followed soon after by a fracture and as deformation occurs; internal intermolecular forces arise that oppose the applied force. If the applied force was not too large, these forces may be sufficient to completely resist the applied force, allowing the object to assume a new equilibrium state and to return to its original state when the load was removed. A larger applied force may lead to a permanent deformation of the object or even to its structural failure.

The number of cycles to failure (N_f) values in the S-N curves with the specimens at the 200 MPa were compared with those with standard size specimens of solution DHP copper tube tested in high temperature. As seen in Figure 8, the number of cycles to failure (N_f) values with the specimens were equal to or slightly greater than those with standard smooth bar specimens. No strong effect of specimen size on the number of cycles to failure (N_f) was found for this specimen. It can be said that the number of cycles to failure (N_f) of the Two-wave type specimen at 573 K, hourglass shaped specimen was rather sensitive to fatigue motion during testing (cyclic tension-compression loading). On the other hand, it was rather insensitive to the lateral displacement and the increase temperature will affect to the structure of copper tube which caused the material damage occurs quickly. Most materials expand somewhat when heated through a temperature range that does not produce a change in phase. When the added heat increases, the average amplitude of vibration of the atoms in the material will increases with the average separation between the atoms. Suppose an object of length undergoes a temperature change of magnitude, if temperature difference was reasonably small, the change in length was generally proportional to length and temperature difference. Stated mathematically; this, of course, that the material will have the same expansion in all directions for a given temperature change. This was true for each of the copper tube materials that we will be using (materials that exhibit this type of behavior, was called linear expansion), so linear expansion have effect to copper tube specimen when increased temperature. From S-N Curve found that the One-wave type specimen at room temperature has the highest the number of cycles to failure (N_f) value because at normal temperature, the structure of copper tube has a few changing that able to bear the fatigue life more than specimens tested at 473 and 573 K and when there were changes hourglass shaped specimen, it will be extended to the fatigue specimen with the Two-wave type specimen components and Uniform-type specimen. The results showed that the effect was a direct extension of the specimen and Hourglass shaped as found the temperature has the greatest impact and then focus on part of the specimen test group compared with the curve of the DHP copper of the stress 200 MPa, the number of cycles to failure (N_f) value was similar. By the properties of copper tube (C1220) with deoxidized high phosphorus copper (DHP copper) was similar, so it was to be in the same range and used the information for applications in the future device. This was particularly important development in the future.

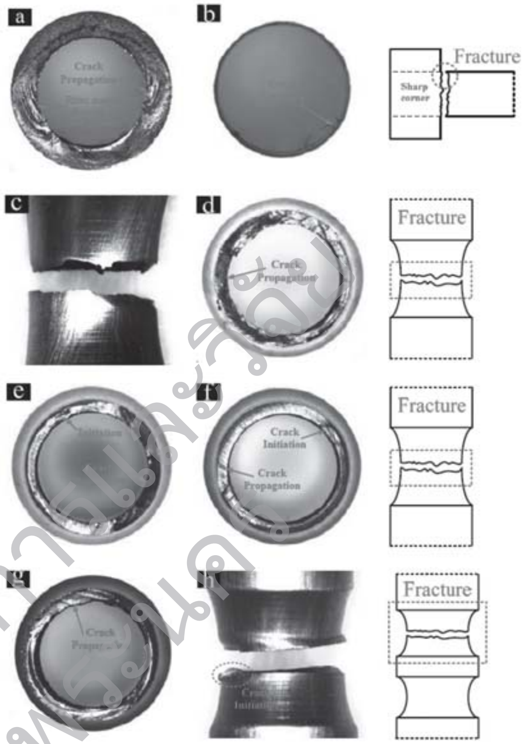


Figure 9 Fracture Surfaces of the Specimens (Flange-model)

3.2 Photographs Observations on the Fracture Surface of the Specimens

Photographs observations on the fracture surface of the specimens, failed at different temperature levels, reveal that different crack propagation operate at different levels of the temperature, as shown in Figure 9(a-h). The specimen surface was measured using photographs taken by the CCD video camera. The crack initiated at the all specimen surface and propagated. The crack surface was observed to be almost perpendicular to the loading direction. Fatigue striations were observed on the surfaces. The fracture surfaces of the miniaturized specimens were similar to those of the standard size specimens. Figure 9(a) and (b) shows the fracture surfaces obtained of the flange-model specimen at relatively stress levels of 200 MPa of the Uniform-type specimen at 293 K. On a macroscopic scale, the surfaces in both the figures were oriented normal to the main principal stress (longitudinal axis of the specimen) and exhibit planar topography with gradually increasing roughness as the crack propagates. The region of crack propagation was characterized by smooth and bright fractured surface, vividly captured in Figure 9(a). The area of final fracture was rather small in these cases owing to relatively lower applied stress. The geometry and macroscopic orientation of the fractured surface (tensile) crack propagation (show the crack has grown in fractures where there have been substantial variations in the component stress as the crack grew across the piece) and Uniform type specimen at 473 and 573 K have the same fracture surfaces of the Uniform-type at room temperature but it has the difference at the number of cycles to failure because the temperature affects the structure copper of the linear expansion. The important feature was the shape of the fracture as viewed from the side. If the stress concentration was relatively insignificant, the fracture face will essentially be a flat plane. But if the stress concentration played an important part in causing the failure, such as a sharp corner on a step in a shaft, the fracture face will be curved in that area affected by the stress concentration. The sketch in Figure 9(a) shows a side view of the cross section of specimen and the concave fracture face indicates that there was a serious stress concentration. (If there had been an adequate radius on the specimen and a low stress concentration factor, the fracture face would have been essentially flat, or the failure may not have happened at all) and show the river marks copied from the fracture face of a failed specimen. River marks show up most frequently in the relatively fast-growing sections of the fatigue zone and other than indicating the direction of crack growth, they supply little information that can be used to diagnose the cause of the failure. Figure 9(b) shows the position at the beginning of the fracture in copper tube, the start of a fracture was determined by the cracking tendencies at the tip of the crack. If a plastic deformation flaw existed at the tip, the structure was not endangered because the metal mass surrounding the crack will support the stress. When ductile fracture occurs, (under the conditions for ductile fracture stated above), the crack will initiate and propagate through the material at great speeds (speed of sound) it should be noted that smaller grain size, higher temperature, and lower stress tend to mitigate crack initiation. Larger grain size, lower temperatures, and higher stress tend to favor crack propagation. There was a stress level below which a crack will not propagate at any temperature. This was called then lower fracture propagation stress. As the temperature increases, a higher stress was required for a crack to propagate. Figure 9(c) shows the fracture obtained of the flange-model specimen at relatively stress levels of 200 MPa of the One-wave type specimen on the temperature at 473 K. Figure 9(d) shows the fracture obtained of the flange-model specimen of the One-wave type specimen at 293 K. From the experiment of copper tube at the room temperature was seen that the fracture surface of copper tube, will look the surface does not smooth because the copper have the properties of toughness. When compared to the fracture surface that occurs to the temperature difference. It can be seen from the surface of the fracture of specimen. Figure 9(e) shows the fracture surface in cross section of the One-wave type specimen on the temperature at 473 K. It was found that a closer examination of the failure surfaces provides more information regarding the nature of the fractures and in the condition; the specimens were failed by the classic fatigue crack initiation and growth mechanism. The fatigue striations were clearly evident on the failure surfaces indicating that the crack advanced through the specimen. The clear indication of intersection flow lines over the entire materials surface indicates the extent to which plastic deformation was distributed around the neck specimen region. While necking was seen in the conditions, the nature of the final fracture surfaces was similar with CCD camera. A limited amount of plasticity-induced deformation void formation was apparent and the final failures appear to be relative ductile in nature. Figure 9(f) shows the fracture surface of the One-wave type specimen on the temperature at 573 K. It was found that the fracture of specimens was alike as One-wave type at 473 K but they would be occurring faster because the temperatures used in testing were difference. Because the temperature was affect to the changing of copper structure that caused the specimen be expand, thus it affected to the thickness of specimen. As a result, the One-wave type specimen at 573 K would be fracture easily than One-wave type specimen at 473 K and the number of cycles to failure (N_f) value was less than that. Figure 9(g-h) shows the fracture surface obtained of the flange-model specimen at relatively stress levels of 200 MPa of the Two-wave type specimen on the temperature at 473 K. It was found that, the fracture at the top of specimen shown in figure diagram so in this area was positioned close to the loading. Thus the fracture specimen was easier than One-wave type specimen which cause the value of the number of cycles to failure (N_f) was low and the temperature increase which cause the specimen will be faster fracture and the temperature will affect the value of the number of cycles to failure (N_f).

4. Conclusion

The major results were summarized as follows:

- The temperature and hourglass shaped specimen of the test have effects on the fatigue life of the heat pipe by the Two-wave type specimen was rather sensitive to fatigue motion during testing at the temperature was 573 K and number of cycles to failure was 10393 has the greatest impact.

The factors that influence the fatigue life of structures are such as mean and stress, hourglass shaped and temperature effect. Some methods have been developed for improving the fatigue performance, which is also evaluated. Good quality design and fabrication of a welded structure can significantly affect the fatigue life.

From the comparison to the total fatigue life of the specimen it can be concluded that in the case of specimens tested under the cycle fatigue, the crack propagation phase constitutes the major proportion of the fatigue life and analysis of experimental results may help to define the fatigue strength for a given number of cycles to failure.

5. Acknowledgements

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