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# An Experimental Investigation of Initiation, Propagation and the Fatigue Life of Modified Coach Peel (MCP) Spot Weld Specimens

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**Abstract**

In this paper, an experimental investigation on the fatigue crack growth behavior and the fatigue life of Modified Coach Peel (MCP) specimens are carried out. The MCP specimens with 1 and 1.5 mm thickness and from milled steel are used. The specimens are tested by a 25 kN capacity INSTRON 8802 servo-hydraulic fatigue test machine under the various level loadings with constant amplitudes. During the loading, the crack length and the cycle numbers are measured accurately. The initiation and the propagation of the spot weld specimens are approximately determined by plotting the vertical position of the specimen versus the cycle's curve. The results show that, the initiation and the propagation of the cracks often occurred for thinner plates. The results also indicate that the crack's length for thinner specimens is longer than that of the thicker specimens. It is also found that the crack growth gradually in low level loadings while it is usually growth around the nugget and eventually pull out the nugget for high level loadings.

**Keywords:** Fatigue Life of Modified Coach Peel, Spot Weld Specimens, Fatigue Crack.

## Introduction

Spot welding is one of the oldest welding processes. It can be used on very thin foils or thick sections but is rarely used above 6 mm thickness approximately. It is used in a wide range of industries notably for the assembly of sheet steel vehicle bodies where more than 100 million welds are made per day in Europe alone. High quality welds can also made in stainless steel, nickel alloys, aluminum alloys and titanium for aerospace applications.

The modeling and the predicting of fatigue life of various spot weld specimens has already been experimented and investigated by many researchers. For example see Zhang[1] and reference therein. As spot welding parts in practice are under combined loadings, the researchers such as Hartmann[2], Davidson[3], Radaj[4], Wang and Awing[5], Swellamet et. al. [6], Sheppard and pan[7], Zhang[8] investigated on specimens with different geometries. Since the circumstance of the nugget regarded as a natural crack or an initial flaw, the analysis of the fatigue life prediction of spot welding specimens usually carried out by fracture mechanics approach. The experimental results play an important role in analysis and modeling of spot welding behavior of specimens by fracture mechanics approach.

The results of any numerical model must be in a good agreement with that of the experimental results. Otherwise the models are invalid. Investigations on various spot weld specimens were carried out by Adib et. al. [9] for predicting the fatigue life of the spot weld specimens using the volumetric method. Xin Sun et. al. [10], investigated the size of melting area and the failure mode on the maximum load and the amount of absorption energy of high strength steels. Xin Long et. al. [11], studied the fatigue properties and characteristics of failure of spot weld high strength plates. Byoung–Ho Chio et. al. [12], examined the fatigue life of triple steel plates. S. H. Lin et. al.[13], studied on the modeling of the fatigue crack growth of spot weld joints under the cyclic loading condition. Ning Pan et. al. [14] performed a research study on the prediction of fatigue life of spot welds under cyclic strain range. Hong Tae Kang [15] studied the predicting of fatigue life of spot weld joints by means of structural stress method. P.C.Lin et. al. [16] studied the spot welds failure modes in the state of plane stress.

## Experimental result

### Test specimens

In this research, four types of MCP specimens with different thicknesses are used. The dimensions of specimens are shown in Fig. (1). As shown in the figure the MCP specimens are jointed to other parts with sheets of 1mm-1 mm, 1mm -1.5 mm and 1.5mm - 1 mm thicknesses. The number of test specimens tested under different loading conditions with constant amplitude loadings are 3 at least. The fatigue life of specimens varied from 50,000 to 1,200,000 cycles.

### The condition of welding specimens

The test specimens were prepared by means of spot welding. The condition of welding is as followings:

Current welding : 8 KA

Welding time : 3 seconds

Electrode face diameter : 6-6.5 mm

Material : milled Steel

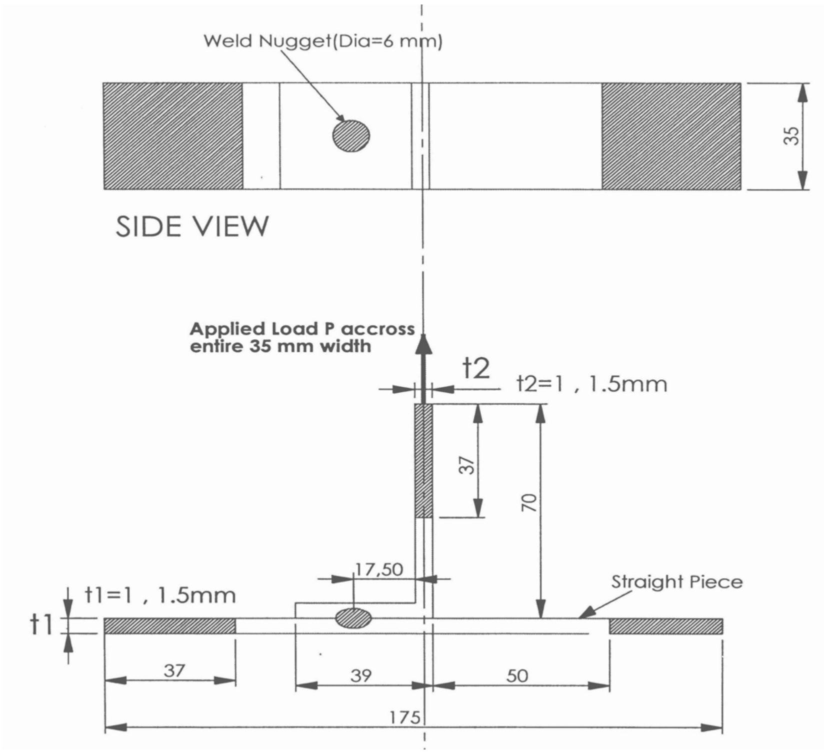



**Figure 1:** Geometry and dimensions of spot weld specimens

**The nomenclature of MCP specimens**

As the sheets with two different thicknesses are used the MCP specimens are divided in four different groups. The specimens are introduced in the form of : MCP**-**-* . Where MCP refers to the type of specimens; the first two digit numbers from the left side indicates the thickness size of L-Sheets (which multiples by 10). The second two digit numbers from the left side is the thickness of straight sheet. The third number refers to the number of specimen in each series. In this investigation, each series have 3 specimens at least.

**Maximum tolerable tensile static force by spot welds**

The nugget diameter was 6 mm (see Fig. 2). The Specimens were experimented by an INSTRON 8802 fatigue test machine(see Fig.3). The tensile strength of the nugget (the maximum tensile force which is tolerable by nugget) was also measured. The mean level of tensile strength of specimens is shown in table 1.

**Material properties**

All the specimens that were used in this research work are milled steels. In order to determine the stress-strain curve, the ASTM standard tensile test of (E8) was achieved by an INSTRON 8802 servo-hydraulic test machine. For each sheet with thickness of 1 or 1.5 mm, two tensile tests was performed. Some of the load -displacement and stress-strain curves are shown in Fig.(5). The maximum of mean tolerable force by

1mm sheet was 4249 N and for 1.5 mm was 6516 N. The width of standard tensile specimen was 12.5mm.

**Figure 2:** Spot weld section on the surface of specimen

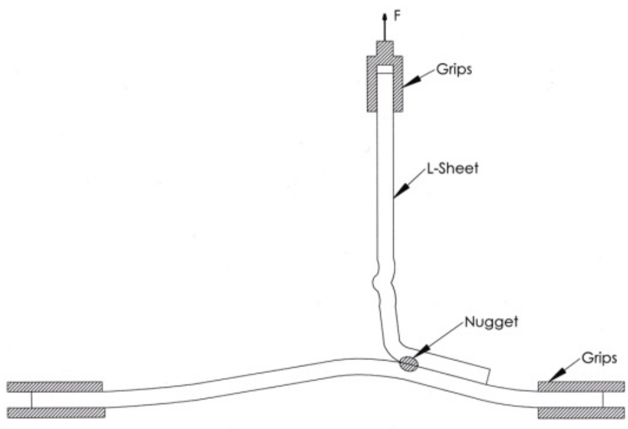



**Figure 3:** Tensile test for determining the tensile strength of nugget.

**Table 1 :** The Mean level of tensile strength of specimens

| Kind of MCP specimens | Tensile strength (N) |
|---|---|
| 1mm-1mm | 2331.8 |
| 1mm(L-sheet)-1.5mm(Flat sheet) | 2420.9 |
| 1.5mm-1.5mm | 2454.3 |
| 1.5mm(L-sheet)-1mm(Flat sheet) | 2115 |

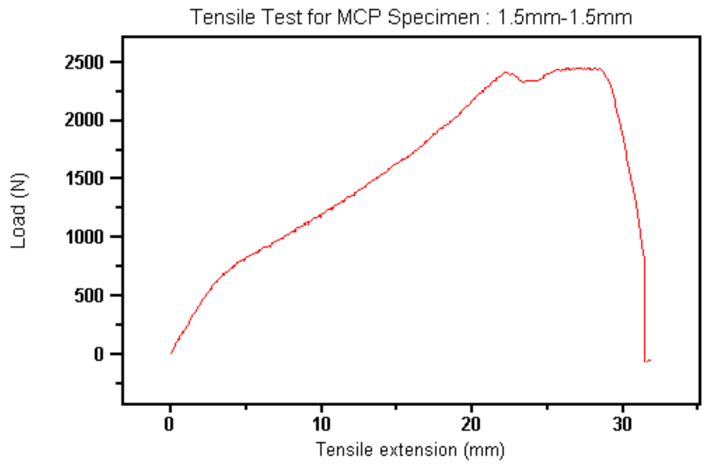
**Fatigue test results**

This research pursuit 3 goals as follows:

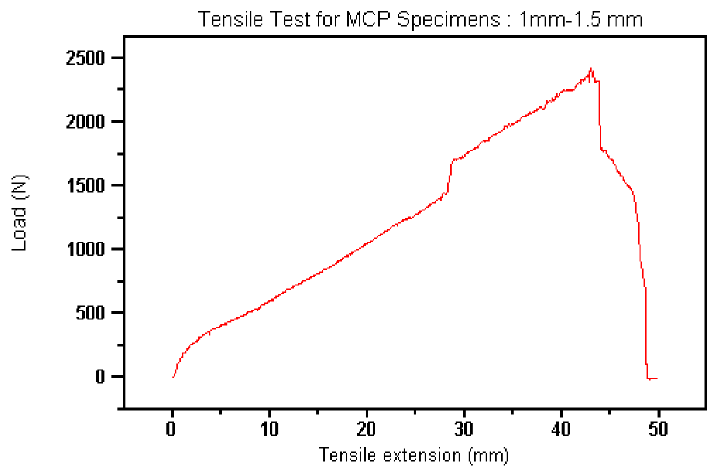
1- The prediction of the fatigue life of specimens

2- The measurement of the crack growth in the transverse side of specimens. (the initiation of the crack length starts wherever the crack was observed on the surface of specimens and terminate until the completeness of the fracture)

3 - The Prediction of the start of fatigue crack propagation




**(a)**

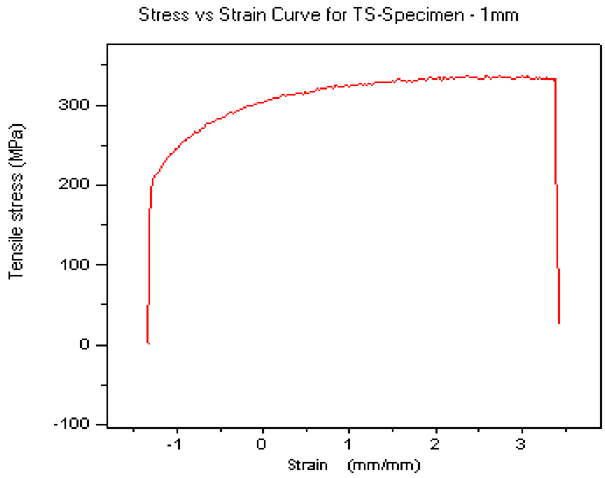



**(b)**

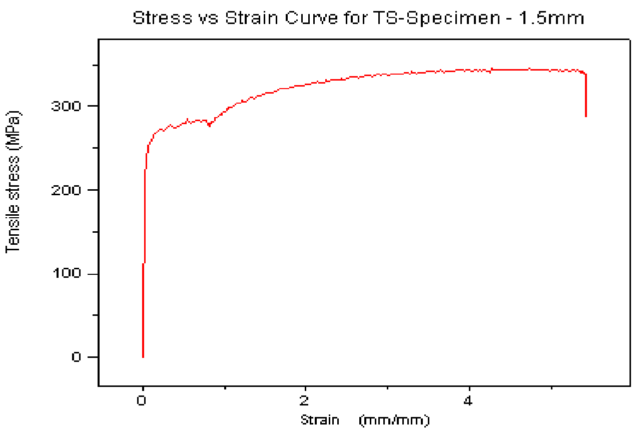
**Figure 4:** Load-Displacement curve of spot weld specimens
(a) MCP 1.5 mm-1.5mm specimens (b) MCP : 1-1.5mm specimens

**Predicting of the fatigue life of specimens**

The fatigue tests were achieved by means of a Servo-hydraulic fatigue test machine, under constant amplitude loading. These are performed in the load-control condition and under the frequency of 10 Hz. Fig.(6) shows the way of locating the specimens in the fatigue test machine. The test results of 4 different kinds of specimens for the load ratio of R=0.1 and R=0.01 are brought in tables 2 and 3, respectively.




(a)




(b)

**Figure 5:** Stress-strain curves for spot weld sheets in uni-axial tensile test
(a) Stress-strain curve for 1 mm thickness sheet, (b) Stress-strain curve for 1.5 mm thickness sheet

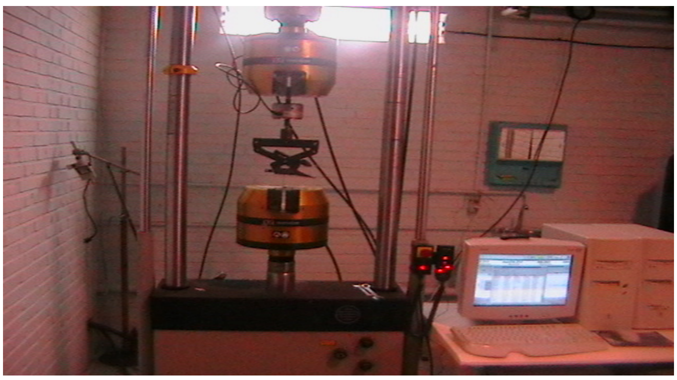


**Figure 6:** Apparatus set up of specimens on INSTRON 8802 Fatigue test machine

**Table 2:** Fatigue test results on the MCP specimens for R=0.1

| Kind of MCP specimens | Maximum applied load (N) | Number of total load cycles applied on each MCP specimens | Observations and crack length in total cycle numbers, $N_t$ |
|---|---|---|---|
| 1mm-1mm | 120 | 1,203,100 | Complete fracture in straight sheet ( according to Fig. 7) |
| | 150 | 549,300 | 2a=15mm in L-Sheet (Fig. 8) |
| | 200 | 191,721 | Complete fracture in L-Sheet |
| | 250 | 92,100 | Complete fracture in L-Sheet |
| 1mm-1.5mm | 150 | 366,287 | 2a=21mm in L-Sheet |
| | 200 | 141,755 | Complete fracture in L-Sheet |
| | 250 | 61,400 | 2a=19.2mm in the L-Sheet |
| | 300 | ----- | ---- |
| 1.5mm-1.5mm | 150 | 1,033,810 | No crack is observed with unarmed eye in the surface of specimen |
| | 250 | 410,000 | Complete fracture in L-Sheet |
| | 300 | 460,000 | 2a=8mm |
| | 400 | 210,000 | Complete fracture in straight sheet |
| 1.5 mm-1mm | 150 | 468,500 | Complete fracture in thin sheet |
| | 200 | 191,292 | Complete fracture in thin sheet |
| | 250 | 94,278 | 2a=19.5mm in thin sheet |
| | 300 | ----- | ------ |

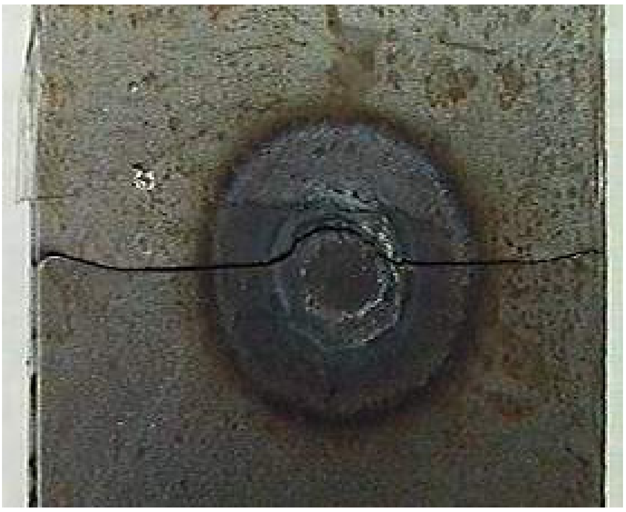


**Figure 7:** Complete fracture of a sheet

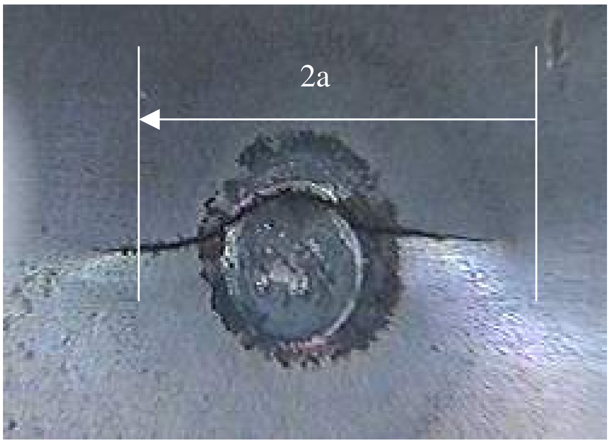



**Figure 8:** Crack in length 2a

The load variation versus the fatigue life for each 4 specimens are shown in Figs (9) and (10) for R=0.1, and R=0.01, respectively. This is related to three fatigue life stages which are t[...] and the fracture stage.

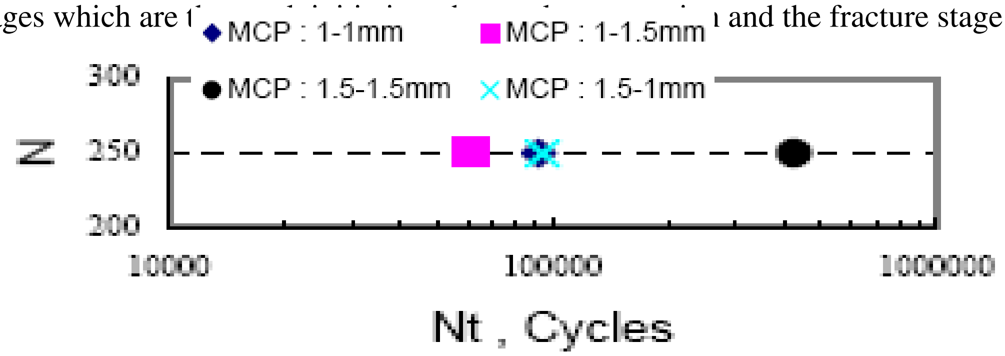



**Figure 9:** Results of load versus fatigue life of spot weld specimens in $F_{max}$=250N

**Table 3:** Fatigue test results on the MCP specimens for R=0.01

| Kind of MCP specimens | Maximum applied load (N) | Number of total load cycles applied on each MCP specimens | Observations and crack length in total cycle numbers, $N_t$ |
|---|---|---|---|
| 1mm-1mm | 120 | 925,831 | Complete fracture in straight sheet. No crack is observed in L sheet |
| | 150 | 343,838 | Complete fracture in straight sheet, a crack with 14 mm length is observed in L-sheet |
| | 200 | 173,981 | Complete fracture in L- sheet, a crack with 22mm length Is observed in straight sheet |
| | 250 | 86,348 | Complete fracture in L- sheet, a 6mm crack is observed in the flat sheet |
| 1mm-1.5mm | 150 | 236,381 | Complete fracture in thin sheet, no crack is observed in L-sheet |
| | 200 | 110,326 | Complete fracture in thin sheet, no crack is observed in L-sheet. |
| | 250 | 12,279 | A crack with 10 mm length is appeared in L-sheet |
| 1.5mm-1.5mm | 250 | 380,808 | Complete fracture in straight sheet, no crack is observed in the L-sheet |
| | 300 | 74,594 | Complete fracture in straight sheet. No crack is observed in L- sheet |
| | 400 | 67,497 | Complete fracture in straight sheet. No crack is observed in L-sheet |
| 1.5mm-1mm | 200 | 217,367 | Complete fracture in thin sheet. No crack is observed in L- sheet |
| | 250 | 34,003 | Complete fracture in thin sheet. No crack is observed in L -sheet |

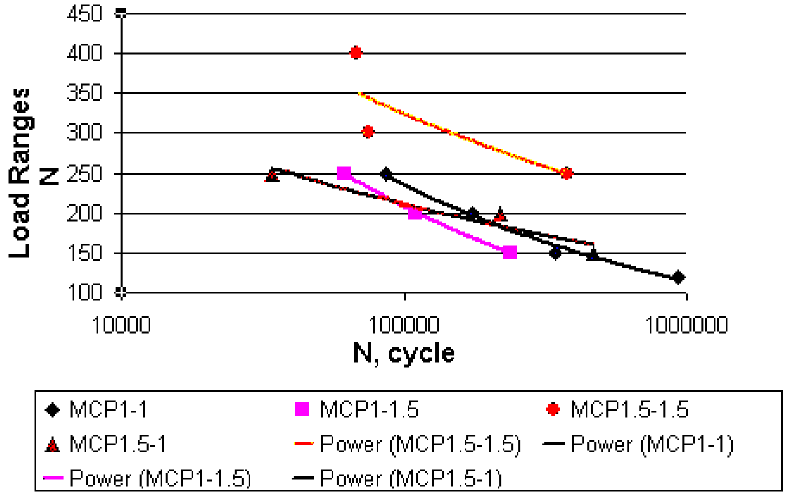



**Figure 10:** Result of load versus fatigue life of MCP spot weld specimens

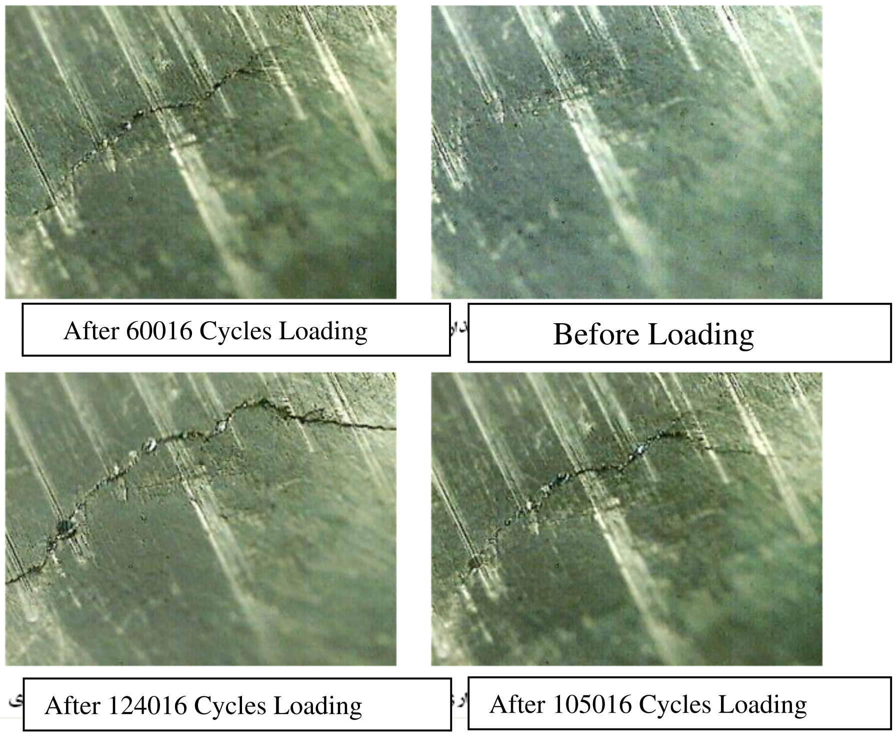



**Figure 11:** Crack growth images in MCP 10-10-4 specimen, during loading.

**measurement of the fatigue crack growth**

Instantaneous testing of the specimens and the observation of the surface of specimens were performed by means of NIKON SMZ-1 microscope with magnification of 100X and a digital camera. In order to see the crack growth obviously the surface of all parts around the nugget were smoothly polished. Also during the loadings, the crack length was measured accurately on the surface of specimens by means of lines that was created by a precision coulisse in 1mm distance from each others.

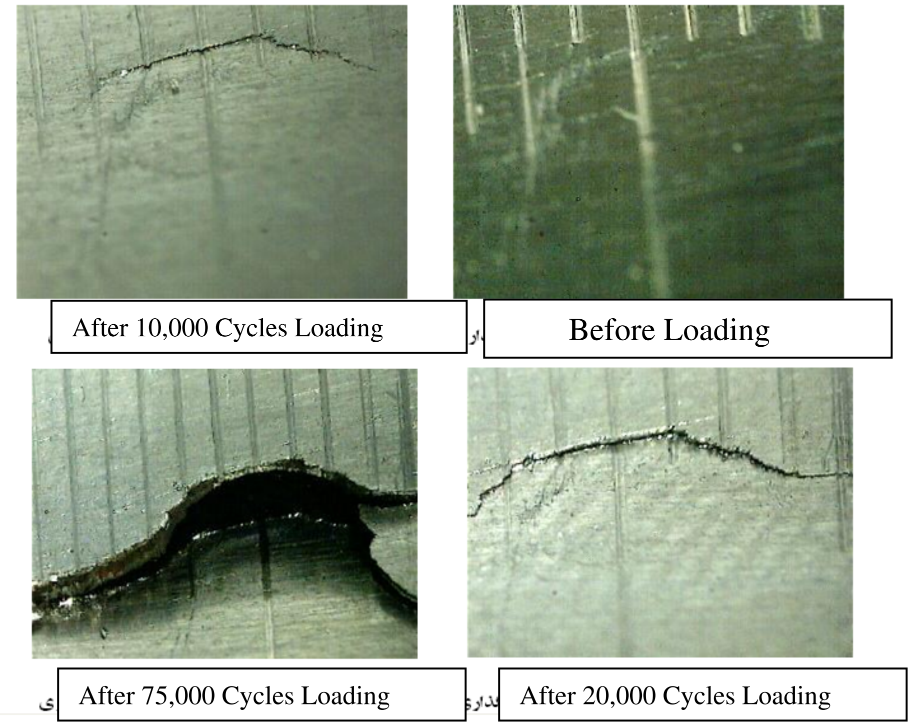



**Figure 12:** Crack growth images in MCP 10-15-1 specimen, during loading

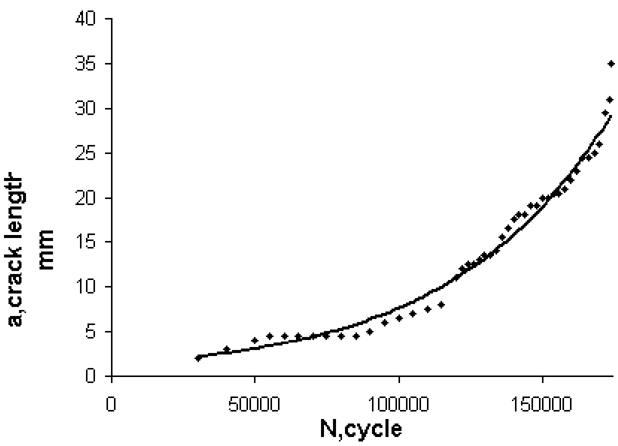



**Figure 13:** Crack length versus the number of cycle curve for specimen MCP 10-10-3

In Figs (11) and (12), some images of the crack growth on the surface of L -shape sheet are displayed. The cracks occur in straight sheet. Since the straight sheet was placed in the lower parts and the crack growth is invisible, the measurement of the crack length is impossible.

The crack length in specimens for the number of specified loading cycles are recorded in a table. The curve of crack length versus the number of loading cycles for specimens MCP 10-10-3, MCP 10-10-4, MCP 10-15-1, and MCP 10-15-3 are observed in figures 13-16.

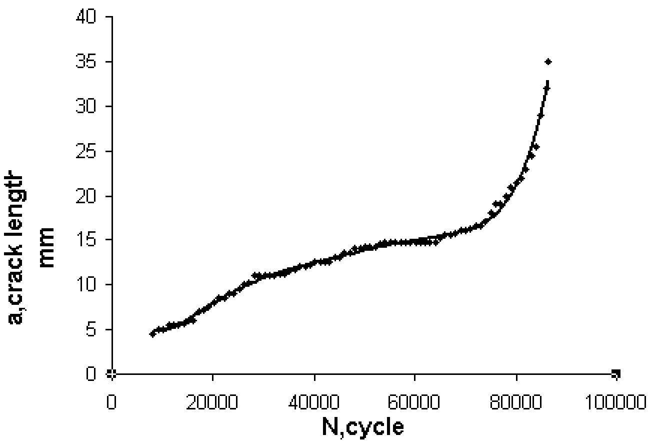



**Figure 14:**Crack length versus the number of cycle curve for specimens MCP10-10-4

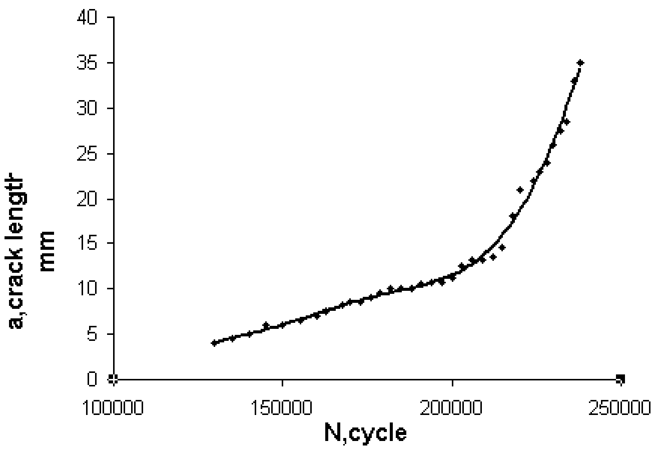



**Figure 15:**Crack length versus the number of cycle curve for specimens MCP10-15-1

In comparing of these two curves, a relation between the crack length, a, and the number of loading cycle, N, for each case can be established. Many useful empirical relations between the parameters such as the changes of crack length with respect to the cycle changes(da/dN) and the amplitude of the stress intensity factor ($\Delta$K) are now possible to establish. In other words,

$$\frac{da}{dN} = c(\Delta K)^m$$

where, m and c are constants.

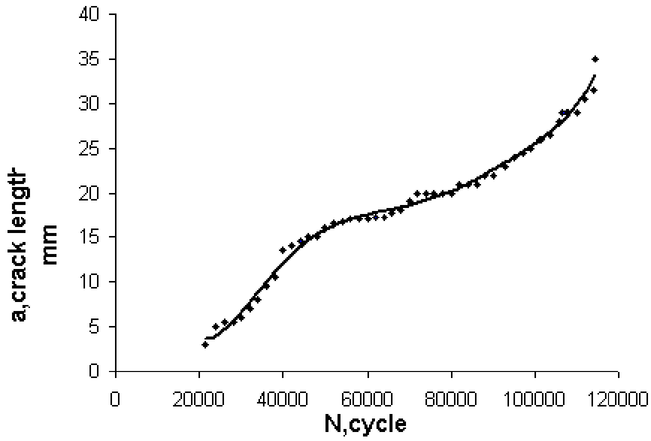



**Figure 16:**Crack length versus the number of cycle curvefor specimens MCP 10-15-3

The preceding relation plays an important rule for predicting the fatigue life of specimens. The relations between the crack length and the fatigue crack growth versus the number of loading cycles for some specimens can be modeled as follows.

The relation of the crack length versus the number of loading cycle for MCP 10-10-3 specimen is set up as:

$$a = 1.2536e^{2*10^{-5}N}$$

The relation of the crack length with respect to the fatigue cycle for MCP 10-10-4 specimen is introduced as

$$a = 5\times10^{-27}N^6 - 1\times10^{-21}N^5 - 7\times10^{-12}N^3 + 2\times10^{-7}N^2 - 0.0018N + 11.075$$

The relation of the crack length as a function of the fatigue cycle for MCP 10-15-1 specimens is introduced as:

$$a = -2\times10^{-28}N^6 + 2\times10^{-22}N^5 - 1\times10^{-16}N^4 + 2\times10^{-11}N^3 - 3\times10^{-6}N^2 + 0.2018N - 5726.8$$

The relation of the crack length as a function of the fatigue cycle for MCP 15-15-3 specimens is found to be:

$$a = 2\times10^{-28}N^6 - 8\times10^{-23}N^5 + 2\times10^{-17}N^4 - 2\times10^{-12}N^3 + 8\times10^{-8}N^2 - 0.0011N + 4.2174$$

By applying the derivative operator on both sides of the above formulas with respect to N the following experimental models for the fatigue crack growth rate as a function of the number of loading cycles for the above specimens are obtained.

$$\frac{da}{dN} = 2.51\times10^{-5}e^{2\times10^{-5}N}$$

$$\frac{da}{dN} = 3\times10^{-26} N^5 - 5\times10^{-21} N^4 - 2.1\times10^{-11} N^2 + 4\times10^{-7} N - 0.0018$$

$$\frac{da}{dN} = -1.2\times10^{-27} N^5 + 1\times10^{-21} N^4 - 4\times10^{-16} N^3 + 6\times10^{-11} N^2 - 6\times10^{-6} N + 0.2018$$

$$\frac{da}{dN} = 1.2\times10^{-27} N^5 - 4\times10^{-22} N^4 + 8\times10^{-17} N^3 - 6\times10^{-12} N^2 + 1.6\times10^{-7} N - 0.0011$$

During the tests, the curves of the vertical displacement of s pecimens versus the number of loading cycles are obtained. This helps to find an appropriate relation between these curves and the fatigue crack length. An example of these curves is shown in Fig.(17). As shown in the figure the behaviors of the two curves are the similar.

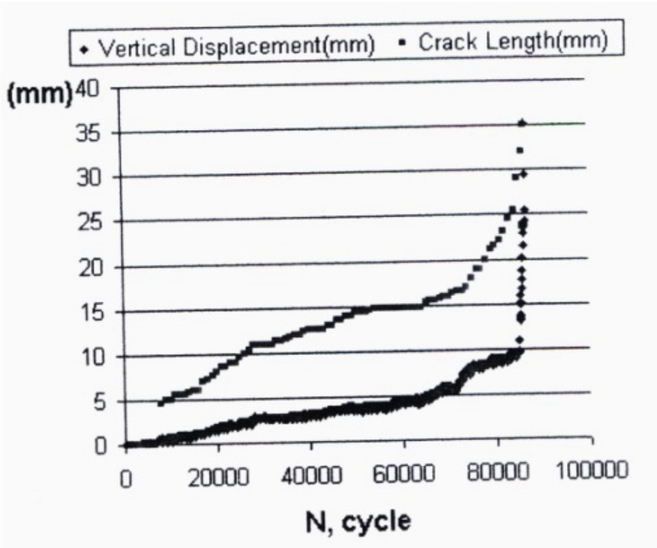



**Figure 17:** Comparison between the crack length and vertical displacement curves for MCP 10-10-4 specimen

### The Prediction of the fatigue crack initiation

Fig.(18) shows the curve of load versus the number of loading cycles for MPC2 : 1.5mm-1.5mm specimen. As shown in the figure there are some variations in the upper and lower limits of the load. This is owing to the low levels of loading and low stiffness in MCP specimens. The figure also indicates that the mean values remain constant approximately. Fig.(19) shows the displacement versus the number of loading cycles of MCP2 : 1.5mm-1.5mm specimen. As shown in the figure the curve is horizontal at first but at 10,000 cycles the shape of the curve is changed and the curve's slope become positive. This point at which the slope changes may be regarded as the initiation of the crack propagation.

Fig.(19) also shows the load versus the number of loading cycle curve for MCP : 1mm-1.5mm specimen. Fig. (21) also shows displacement versus the number of loading cycles curve for MCP : 1mm-1.5mm specimen. As seen in the figure the crack initiates at the 40,000 loading cycles approximately.

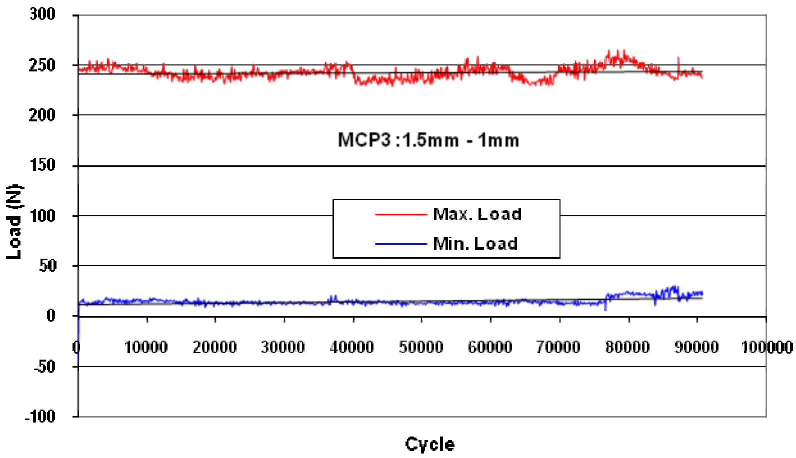



**Figure 18:** The load versus the number of loading cycles curve for for MCP : 1.5mm-1.5mm specimen

Fig.(19) also shows the load versus the number of loading cycle curve for MCP : 1mm-1.5mm specimen. Fig. (21) also shows displacement versus the number of loading cycles curve for MCP : 1mm-1.5mm specimen. As seen in the figure the crack initiates at the 40,000 loading cycles approximately.

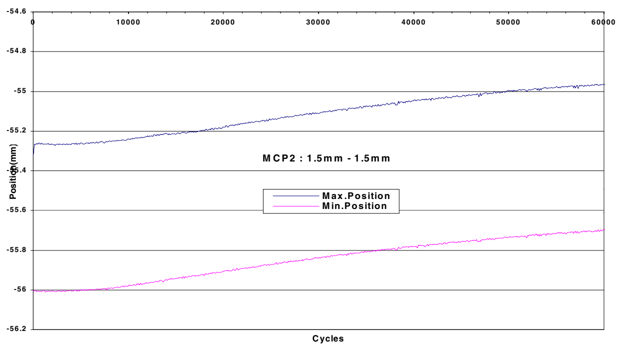



**Figure 19:** The displacement versus the number of loading cycles curve for MCP : 1.5mm-1.5mm specimen

Fig. (22) also displays a part of the displacement versus the number of loading cycles curve of MCP : 1mm-1.5mm specimen. As seen in the figure the crack propagation initiates at 60,000 loading cycles approximately. Note that the maximum applied load on this specimen is 150N.

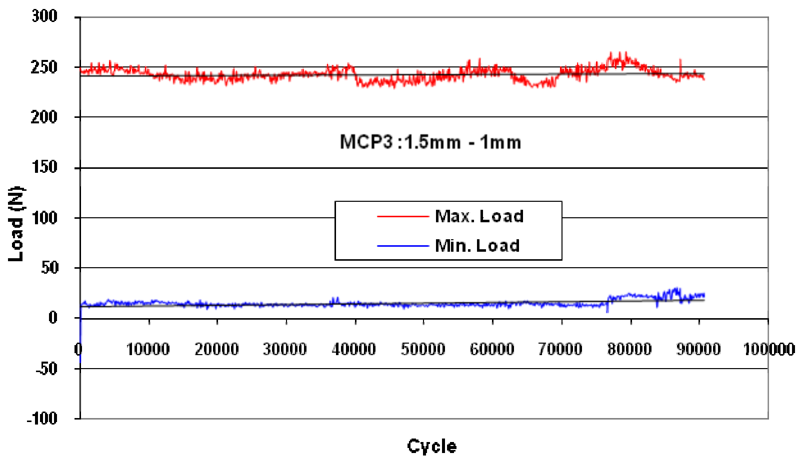



**Figure 20:** The load versus the number of loading cycles curve for for MCP : 1mm-1.5mm specimen

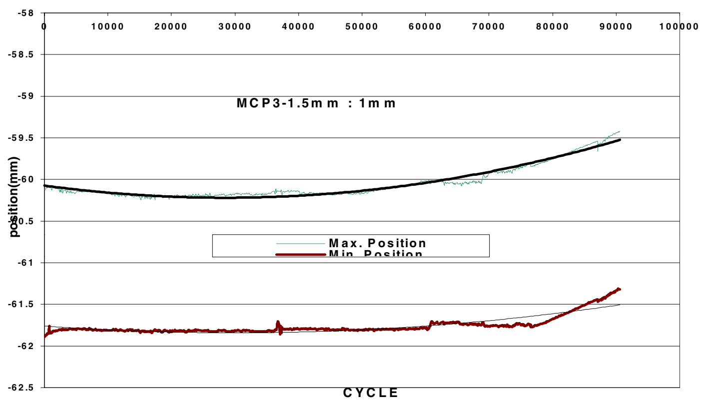



**Figure 21:** The displacement versus the number of loading cycles curve for MCP : 1mm-1.5mm specimen

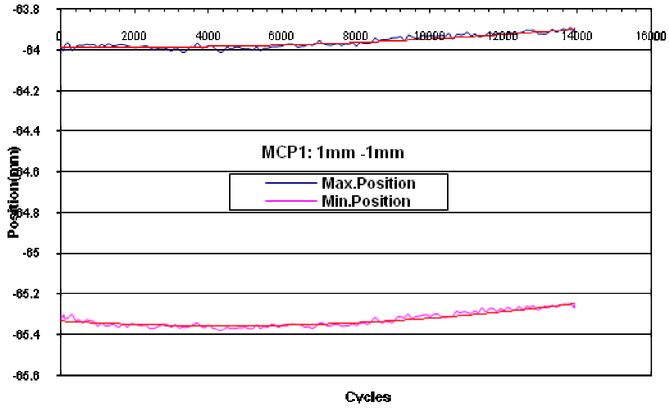


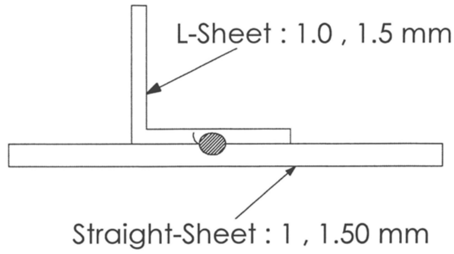

**Figure 22:** The displacement versus the number of loading cycles curve for MCP : 1mm-1mm specimen

## Results and discussion

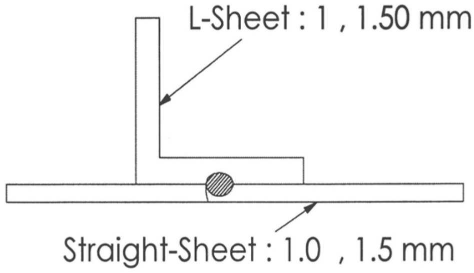
The results of the experimental investigations conducted in this work can be summarized as follows:

1- In table 4 the fatigue life of the crack reached to the surface of specimen, $N_{p,}$ and the total fatigue life of the crack, $N_{t,}$ are given. The data indicate that 50% of the total life of the specimen belongs to the initiation and propagation stages in the bulk of the long life specimen (low levels of loading). This percentage for short life specimen ( high levels of loading) is 16.5%.
2- The fully growth cracks are suddenly reached to the external surface of specimens so that the it is impossible to measure the small crack length (less than 2 mm in length). The cracks with the length of 2.5-4 mm are observed in the external surface of specimens.
3- The cracks observed at the external surface are located around the nugget and oriented towards the vertical edge.
4- Cracks propagate around the nugget as an arc shape first. The cracks are then continue in the direction of the parallel to the vertical edge until the fracture occurs.
5- According to Figs 23-25 the initiation and the propagation of cracks for all the specimens are observed around the nugget and in the positive side of the applied tensile stress.
6- The crack initiation and propagation always occur in the thinner sheets (see Figs 23,24).

Figs 24(a) and 24(b) shows a specimen with a thickness of 1.5 mm L-sheet and a 1.0mm thickness of straight sheet. The figure shows that the crack appears in specimen with less thickness only. No crack growth is observed in the thick sheet. Fig. 24 (c) and 24(d) show a specimen with a thickness of 1.0 mm L-sheet and the thickness of 1.5mm straight sheet. The figure shows that the cracks are appeared in thin sheet only and there is no crack in the thick sheet.

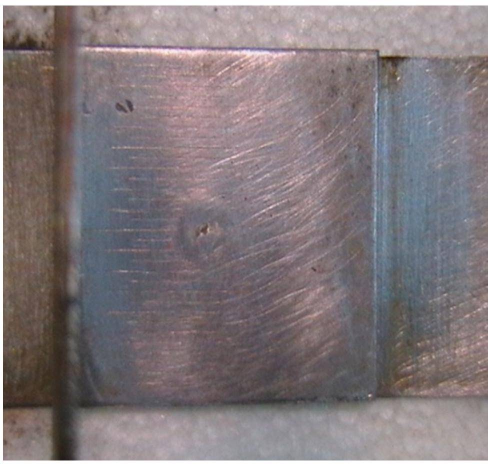



**(a)**

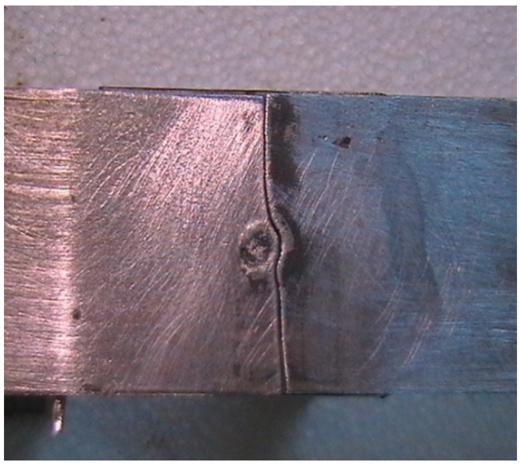



**(b)**

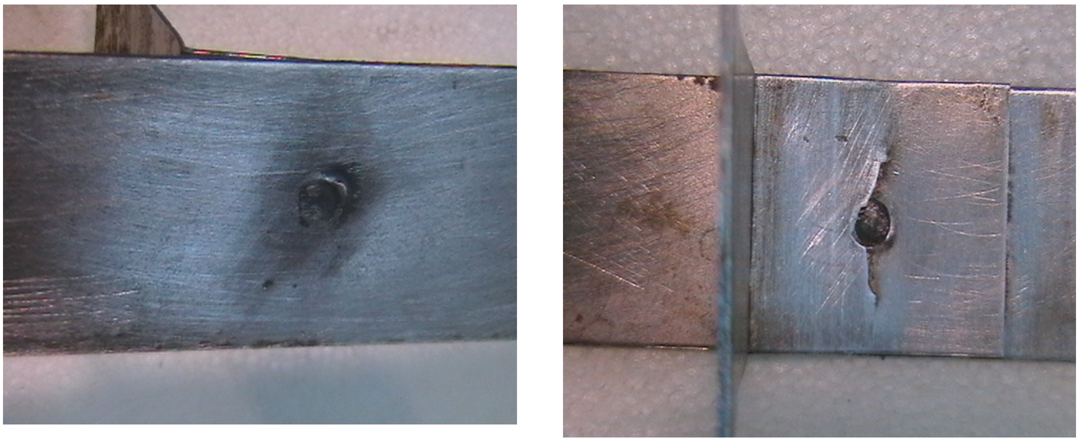
**Figure 23:** Location of crack initiation and propagation around the nugget. In both cases, initiation and propagation of crack is occurred in thinner sheet.



**b: in L-sheets with 1.5 mm thickness, there is not crack**



**a: manner of crack growth in straight sheet with 1.0 mm thickness**



**d: there is no crack in straight sheet**

**c: manner of crack growth in L-sheet with 1.0mm thickness**

**Figure 24:** manner of crack growth in U-shape specimens

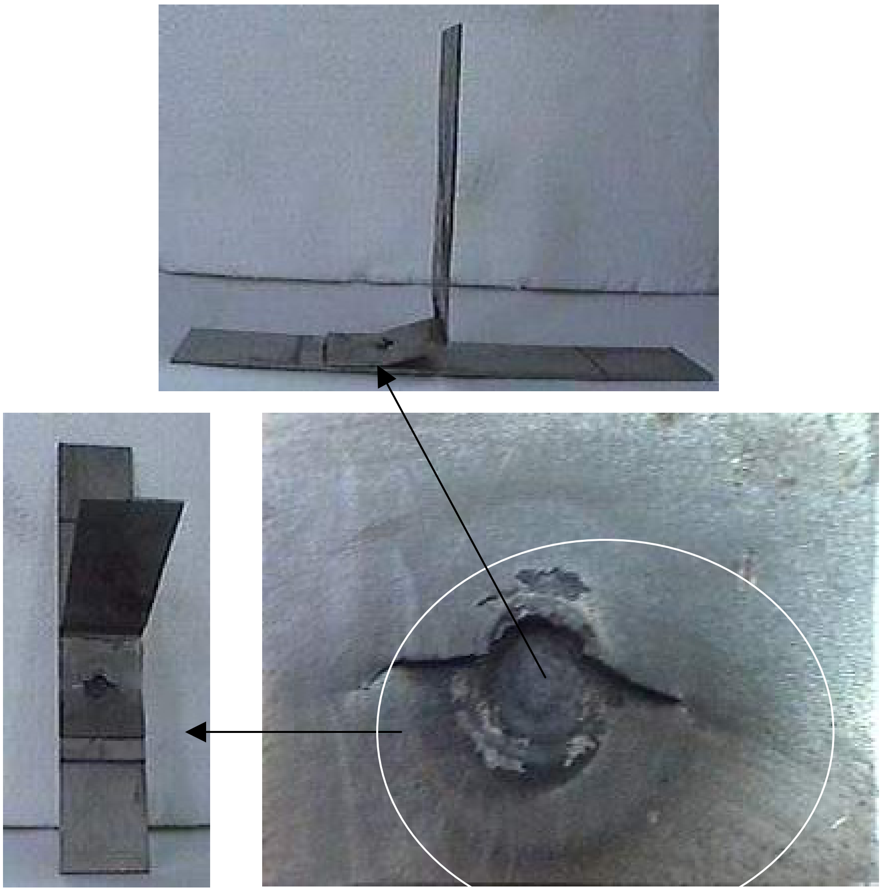


**Figure 25:** Location of initiation and propagation of a crack in a real specimen

**Table 4:** Fatigue crack life of some specimens in initiation and propagation stages, till became visible on surface for R = 0.01

| **Kind of MCP specimen** | **Maximum load(N)** | **Number of cycles till the crack became visible on surface , $N_p$** | **Total fatigue life, $N_t$** | $\frac{N_p}{N_t}\times 100$ |
|---|---|---|---|---|
| 1mm-1mm | 150 | 173,426 | 343,838 | 50.44 |
| | 200 | 30,000 | 173,981 | 24.17 |
| | 250 | 8,134 | 86,348 | 42.9 |
| 1mm-1.5mm | 150 | 127,854 | 236,381 | 1.54 |
| | 200 | 21,229 | 110,326 | 24.19 |
| | 250 | 12279 | 61400 | 20 |

## Conclusions

The following results are obtained from the observations and analysis of the surfaces and the fracture sections.

1- In specimens with varying thickness, cracks always start from the thinner part and the final fracture occurs in the thinner part of the sheet.
2- In specimens with uniform thickness, crack appears in both sheets. Fracture in low level loadings (high fatigue cycles) appears in the straight sheet. For high level loadings (low fatigue cycles) fractures appear in the L-sheet.
3- Crack propagates in an arc shape around the nugget and the final fracture occurs in the sheet only. The fracture does not occur in the nugget.
4- In specimens with varying thickness crack always initiates and propagates in the thinner sheet.
5- In specimens with uniform thickness cracks always appear in L-sheets. It sometimes appears in flat sheets with cases in tables 2 and 3.
6- The crack length in sheets with uniform thicknesses remains the same approximately for both specimens.
7- Crack initiates around the nugget for low level loadings. It spreads considerably inside the sheet until the final fracture occurs. As the load level increased, the crack propagation decreased in the sheet so that for relatively high level loadings, the crack propagates a little around the nugget and fracture occurs suddenly.

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