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Fretting fatigue in AISI 1015 steel

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Abstract. **A small oscillatory movement between two contacting surfaces is termed as fretting and on many occasions it acts as the crack initiation site leading to catastrophic failure of the overall structure. The occurrence of fretting is observed in many engineering structures such as shaft flanges, gas turbines, steel ropes etc. An experimental facility, which can simulate the fretting fatigue in many engineering applications, is the primary requirement of the research program. A laboratory fretting fatigue test facility capable of varying many influencing parameters of fretting fatigue such as slip amplitude, frequency, contact pressure, etc is designed and developed. Preliminary investigations on plain and fretting fatigue behaviour of AISI 1015 structural steel are reported in this paper. A strength reduction factor of about 1·30 was obtained due to fretting for the test material under the present experimental conditions. Influence of contact load on fretting was also studied. Increasing fretting contact load decreased the fatigue life in the range investigated. Failure analysis showed typical stage I oblique crack growth followed by stage II straight crack perpendicular to the fretting zone.**

Keywords. **Fretting fatigue; contact load; structural steel; failure mechanism.**

1. Introduction

Localized relative motion between machine components under vibratory loads results in early crack initiation and propagation leading to overall failure of the structure even at very low stresses (Waterhouse 1992). This type of failure is termed as fretting fatigue failure and is a serious problem in many industrial applications such as bolted joints, riveted joints, shrink fit shafts, wire ropes, leaf springs, wheel-on-axle assemblies, turbine engines, etc. Many analytical and experimental research on the fretting fatigue behaviour have been carried out in recent years (Waterhouse 1992; Mutoh 1995; Lindley 1997). Fretting fatigue behaviour of many metallic materials, composites and ceramics has been reported. In general, fretting results in the reduction of fatigue strength of the materials. It has been reported by Dobromirski (1992) that there are more than fifty variables that influence the fretting fatigue process. Effects of combination of materials, surface treatments, contact pressure, slip amplitude, and frequency on the fretting fatigue behaviour of many engineering alloys are some of the widely investigated parameters by many researchers (Waterhouse 1992; Lindley 1997). Fretting was found to reduce the fatigue life in all the investigations but the degree of strength reduction widely varied due to many influencing parameters and the test methodology followed (Lindley 1997). Fretting fatigue behaviour of high-strength steel was reported by Tanaka *et al* (1985). Influence of contact pressure on fretting fatigue life was also reported by some investigators on different materials (Nakawawa *et al* 1992; Satoh 1992). Fretting life was found to decrease monotonously in steel and titanium specimens at higher stress amplitudes. Most of the research were performed using servo hydraulic test machines on tensile specimens with modifications for introducing contact loads on the gauge section. Rotating bending fatigue test machines were also employed for studying the fretting fatigue by some investigators (Satoh 1992; Li *et al* 1999). Fretting fatigue behaviour of ceramic materials was also studied using three-point bend specimens (Okane *et al* 1994). Cantilever bending fatigue test machines were used by many investigators as it was possible to vary many influencing parameters of fretting fatigue easily in these machines (Takeuchi *et al* 1994).

This paper describes the test facility developed as a part of the research program for investigating the fretting fatigue behaviour of surface modified steels. Some preliminary investigations carried out on the fretting fatigue behaviour of as-received low carbon structural steel are reported. Micromechanisms of failure are also studied.

2. Fretting fatigue test rig

As the future research programs on fretting fatigue planned at the laboratory involved fretting occurring on the members subjected to bending, it was planned to design and develop a cantilever bending type test machine

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capable of simulating those situations. In the bending fatigue test machine developed it is also possible to vary most of the influencing fretting fatigue parameters such as slip amplitude, contact pressure, frequency etc to the required levels. In addition, the design and fabrication of the machine is also relatively easier compared to other machines.

As there are no standards available for the fretting fatigue testing methods and specimens design it is decided to use a similar geometry proposed in the ASTM standard for bending fatigue. For most of the metallic materials under consideration, a maximum bending stress of about 300 MPa is quite sufficient for failure with the presence of fretting. Therefore, a design for developing a bending stress of about 1000 MPa is sufficient for the materials under consideration. Another important parameter in the fretting test machine is the clamping pressure or contact load. A design for exerting contacting pressures up to 1000 MPa is more than sufficient for simulating most of the practical problems. It is also widely reported that most of the fretting failures are severe when the slip amplitude is in the order of few tens of microns and in many practical instances it may vary to few hundred microns also. The frequency of testing is another important design parameter. Most of the research work was done on the frequencies of about 10 Hz.

The schematic of the cantilever type bending fatigue test machine designed and developed for the current research program is shown in figure 1. The test rig assembly consists of three modules: drive module, specimen-pad assembly module and loading and instrumentation module. The drive module consists of a d.c. motor mounted on rigid base to enable fretting fatigue studies at different frequencies. By varying the speed of the electric motor it is possible to get the specimen frequency ranging between 0 and 33 Hz, in which most of research is performed. The drive motor is connected to the main shaft by means of double V-belt drive in order to avoid transfer of motor vibration and noise to the specimen-pad assembly. The bending specimen is connected to the eccentric by means of connecting lever through rod end bearing and linear bush. The eccentric positions are calibrated and marked to give different bending stresses on the specimen to be tested. Figure 2 shows the contact pads and bending specimen assembly. The movements of the pads of bending specimen is shown by arrows. A pair of contact fretting pad is clamped to the specimen using a proving ring. Contact pads are fixed to the fretting arms, which are driven by another lever connected to eccentric wheel. The fretting pad movement can be varied by adjusting the eccentric position. The designed eccentric permits the horizontal movement of the pad to a

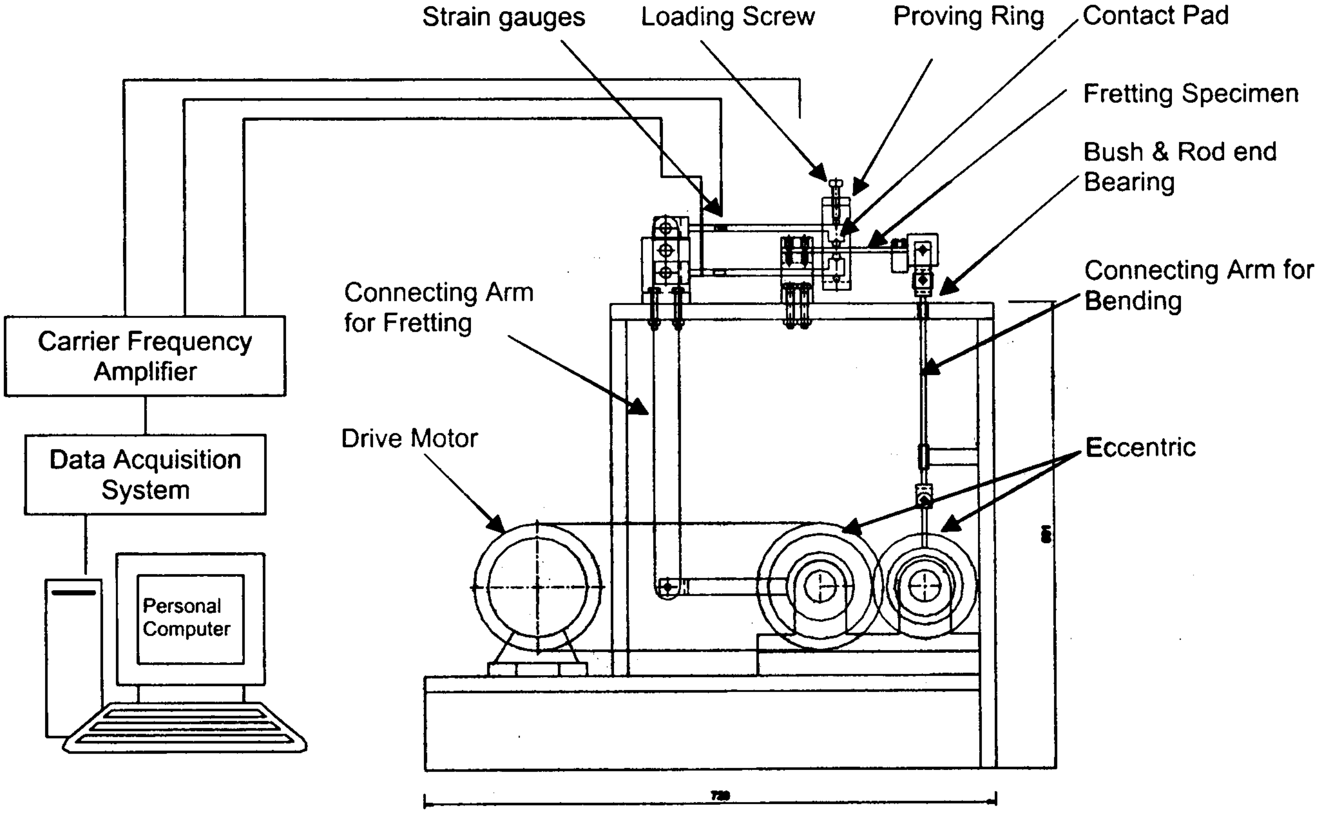

Figure 1. Schematic of the cantilever bending type fretting fatigue test machine designed and developed in the laboratory.

maximum distance of 250 μm. The relative slip amplitude between the pad and specimen is measured and kept constant for the current set of experiments to a value of 50 μm. The eccentric wheel for fretting motion is connected through a pair of gear wheels to the same drive motor. The frictional force between specimen and contact pad is measured by using a strain gauge attached to the fretting arm, which was calibrated by applying tensile and compressive loads. The contact pressure between the specimen and contact pad is adjusted by proving ring. All the data are continuously monitored and stored using the personal computer based data acquisition system.

3. Test materials and experimental procedure

3.1 *Test materials*

Fretting fatigue specimens were made from as-received AISI 1015 structural steel. All the sides were polished using #800 grade emery paper and degreased using acetone bath in ultrasonic cleaner. Contact pads were machined to the dimensions, polished and degreased. The chemical composition of test and contact pad materials is shown in table 1. The surface roughness of the specimens and pads was measured using a perthometer. Table 2 shows the surface roughness values of specimen and contact pad.

3.2 *Experimental*

The bending specimen similar to the one recommended by the ASTM standard for bending fatigue was used in the current investigations. The specimen and pad dimensions used for the current research program are shown in figure 3. Cylindrical contact pads of the dimensions shown in figure 3 were used. Both plain and fretting fatigue tests were conducted on specimens made from as-received material. Experiments were performed at a constant frequency of 10 Hz at room temperature air atmosphere. Plain bending fatigue strength of as-received material was estimated using standard fatigue test procedures at a constant stress ratio of – 1 and zero mean load. Specimens were run up to failure or up to 2 million cycles whichever was earlier. Fretting fatigue tests were performed using the carefully prepared fretting specimens and contact pads, which were cleaned in acetone bath using an ultrasonic cleaner. Required slip amplitude and bending stress were set using the corresponding eccentrics. Contact load was set to the required level using the loading screw. Fretting fatigue tests were performed at a constant contact load of 250 N. Fretting tests were also carried out at different contact loads to

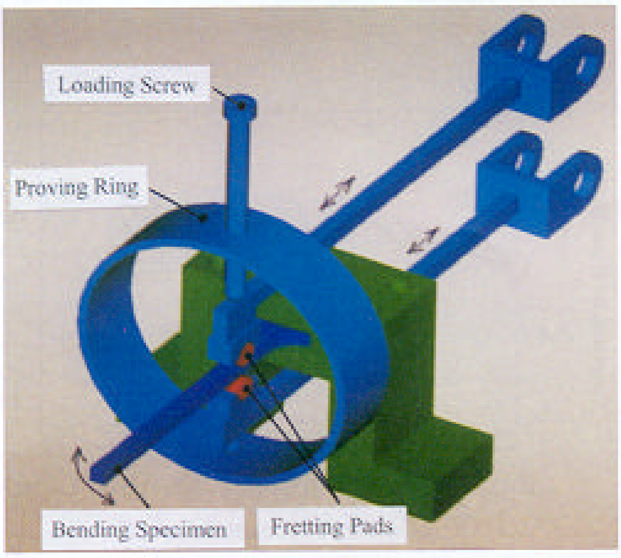

Figure 2. Model of the fretting pad and specimen assembly used in the set up.

Table 1. Chemical composition of the specimen and pad (weight %).

	C	Si	Mn	P	S	Fe
Specimen	0·15	0·13	0·39	0·05	0·05	bal
Contact pad	0·15	0·21	0·49	0·03	0·02	bal

Table 2. Surface roughness of the bending specimen and contact pad.

	Surface roughness		
	R_a (μm)	R_{max} (μm)	R_z (μm)
Bending specimen	0·03	3·34	2·02
Contact pad	0·04	3·21	2·07

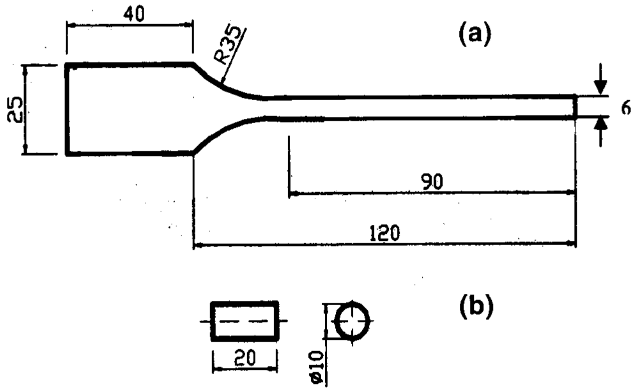

Figure 3. Geometry of (**a**) bending specimen (thickness = 6 mm) and (**b**) contact pad. (All dimensions are in mm).

study the effect on the fretting load in the same material. In order to understand the micro mechanisms of failure, subsurface analysis was carried out using optical microscopy and image analyser.

4. Results and discussion

4.1 *Plain fatigue behaviour*

The plain bending fatigue behaviour of AISI 1015 steel together with the fatigue curves of other structural steels obtained from literature are shown in figure 4. The fatigue behaviour of the test material is superior to that of the EN 320 steel because of the high hardness of the current test material compared to the material reported (Ramalho *et al* 2000). However, the alloy steel with high strength EN 19 (Li *et al* 1999) showed superior behaviour compared to the low strength test material. The results confirm the satisfactory performance of the test machine giving acceptable values. The endurance limit fatigue strength at 2 million cycles for the test material is 370 MPa.

4.2 *Fretting fatigue behaviour*

Fretting fatigue behaviour of the test material is investigated at a constant contact load of 250 N. Results are shown in figure 5 together with plain fatigue data. The endurance limit strength under fretting fatigue is about 285 MPa while without fretting it is about 370 MPa resulting in the stress reduction factor of 1·30. A reduction factor ranging from 1·1 to 4 was reported in the published literature under fretting fatigue (Waterhouse 1992; Lindley 1997). The wide variation in the values is mainly due to the different variables influencing the fretting behaviour and method of testing.

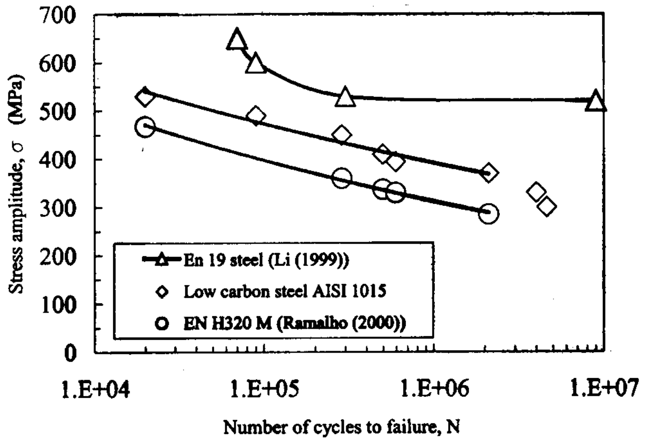

Figure 4. Plain bending fatigue behaviour of AISI 1015 steel together with the fatigue curves of other structural steels.

Typical values of the on-line frictional force recorded during the experiments are shown in figure 6. In all the cases the friction coefficients are very high ranging in the order 0·50–0·62. During the beginning of the experiments the values were around 0·50 and later it increased to 0·62 and remained more or less constant. An increase in the frictional force was observed when the fretting scar was developing. Generation of fretting debris during the beginning of the experiments are mostly the oxide particles which are very hard in nature and try to remain in the fretting zone resulting in the increase of the friction coefficient. The friction coefficient remained approximately same after this initial increase throughout the experiment up to crack initiation. The average friction coefficient values measured after the friction coefficient reached the plateau region is plotted against the stress amplitude in figure 7. No significant variation in the friction values measured was observed by varying the bending load amplitude.

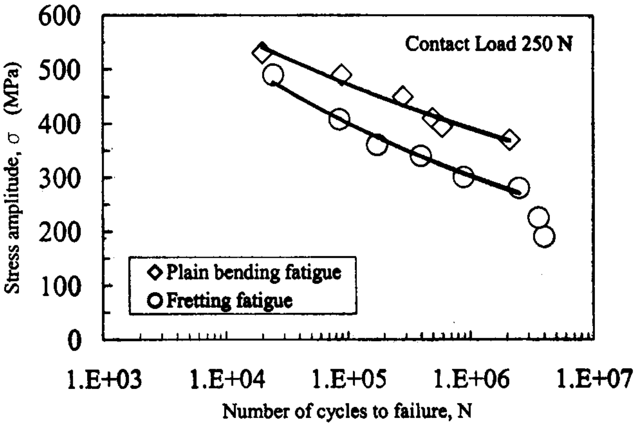

Figure 5. Plain and fretting fatigue behaviour of AISI 1015 steel.

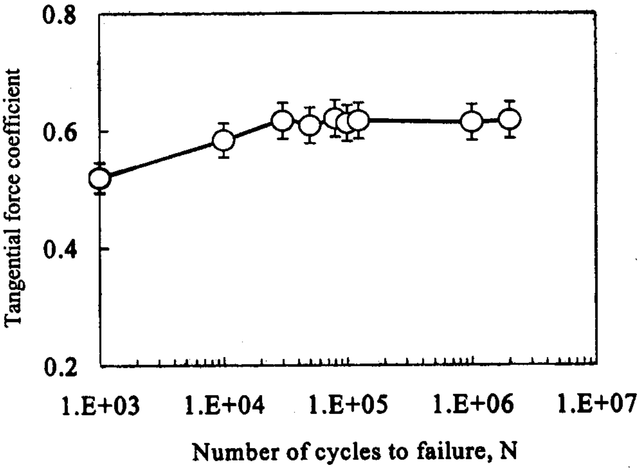

Figure 6. Variation of the tangential force coefficient during fretting fatigue testing of AISI 1015 steel.

The variation of fretting life as a function of the contact load at a constant bending stress, 350 MPa, is shown in figure 8. During the present investigations the loads are kept constant and this results in the decreased contact stress with increased number of cycles due to fretting contact width increase. The contact stresses are of the order of 40 MPa (due to increase in the wear scar width) at time of failure for the contact load of 191 N. Even at these low contact stresses the specimens failed very early (~ 4 × 10^{-5} cycles) compared to the plain fatigue life (~ 4 × 10^{-6} cycles) showing significant effect of fretting. From these results it seems that even this stress is higher than the minimum contact stress required for fretting in metallic materials.

4.3 *Failure observation*

A large number of cracks were observed in the fretted region of the specimens observed under microscope. In general, two types of cracks leading the final fracture of the fretting specimen were reported (Gnanamoorthy and Rosi Reddy 2000; Lamacq *et al* 1992). Cracks initiated at the fretted region grow obliquely due to combined tangential frictional forces and bending stresses. After it has grown to a certain depth, the crack grows perpendicular to the fretting surface, as the frictional forces are insignificant. Cracks emanating from the fretting zone growing perpendicular to the fretting zone without clear stage I and II types are also reported. In the as received specimens investigated, all the specimens

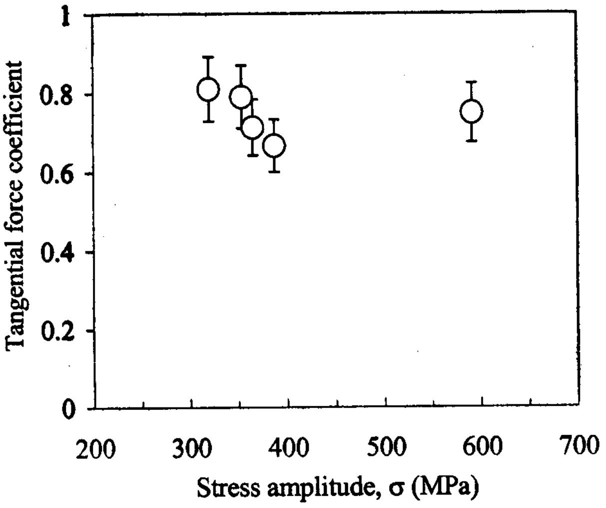

Figure 7. Typical tangential force coefficient at the end of testing at different bending stress levels in AISI 1015 steel.

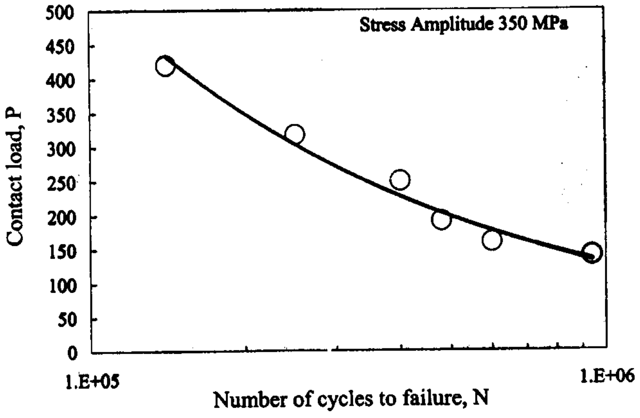

Figure 8. Effect of contact load on the fretting life of AISI 1015 steel.

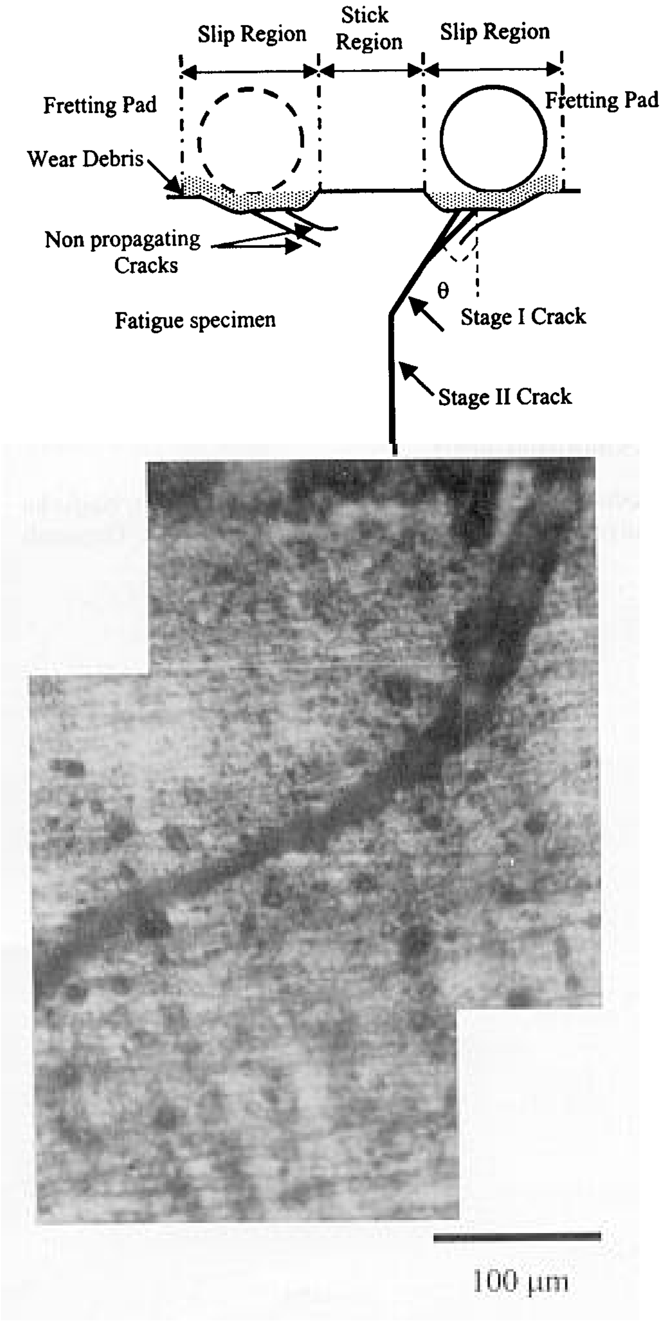

Figure 9. Crack observed in as-received AISI 1015 steel after fretting showing clear stage I and stage II crack.

showed clear stage I and II types crack growth. This is shown in figure 9 together with the schematic figure. The cracks originate at the edge of the fretting zone in all the specimens. Fatigue cracks are initiated under maximum repeated shearing stress which is the combination of tangential stress and applied repeated stress (Endo and Goto 1976). Presence of wear debris also accelerates the crack initiation process in this zone. The stage I crack angle ranges from 12° to 48° and depends on the bending stress and contact load.

5. Conclusions

A cantilever bending type fretting fatigue test rig is developed which is capable of studying the effect of various influencing parameters of fretting fatigue. Influence of fretting on the fatigue behaviour of AISI 1015 structural steel is reported. Fretting was found to reduce the fatigue life of the as-received material. A strength reduction factor of about 1·30 is obtained under the present experimental conditions. Increasing the contact load decreased the fatigue life of the AISI 1015 steel. Fretting cracks originate at the edge of fretting zone growing obliquely up to a particular depth and growing perpendicular to the fretting zone.

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References

Dobromirski J M 1992 in *Standardization of fretting fatigue test methods and equipment, STP 1159* (Philadelphia, USA: American Society of Materials Science) p. 60

Endo K and Goto H 1976 *Wear* **38** 311

Gnanamoorthy R and Rosi Reddy R 2000 unpublished results

Lamacq V, Dubourg M C and Vincent L 1992 *Tribology Int.* **30** 391

Li C, Sun Y and Bell T 1999 *Surf. Eng.* **15** 149

Lindley T C 1997 *Int. J. Fatigue* **19** S39

Mutoh Y 1995 *JSME Int. J. Ser. A* **38** 405

Nakazawa K, Sumita M and Maruyama N 1992 in *Standardization of fretting fatigue test methods and equipment, STP 1159* (Philadelphia, USA: American Society of Materials Science) p. 115

Okane M, Kiyshi Y, Mutoh Y and Suzuki S 1994 *Trans. Jpn. Soc. Mech. Eng.* **60** 1

Ramalho A, Correia L M and Costa J D 2000 *Tribology Int.* **33** 761

Satoh K 1992 in *Standardization of fretting fatigue test methods and equipment, STP 1159* (Philadelphia, USA: American Society of Materials Science) p. 85

Takeuchi M, Satoh T, Mutoh Y, Waterhouse R B and Kon Y 1994 *Fatigue Fract. Engg. Mater. Struct.* **17** 949

Tanaka K, Mutoh Y, Sakoda S and Leadneater G 1985 *Fatigue Fract. Engg. Mater. Struct.* **8** 129

Waterhouse R B 1992 *Int. J. Fatigue* **37** 77