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EFFECT OF GRAIN SIZE ON FRETTING FATIGUE BEHAVIOUR OF AISI 304 STAINLESS STEEL

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Abstract
The present work describes the effect of grain size on uniaxial fatigue behaviour (with and without fretting) of AISI 304 stainless steel. Coarse grained (137 μm) material exhibited longer fatigue lives at low cyclic stress levels compared to fine grained (43 μm) material. This was attributed to the formation of more martensite in the coarse grained material. Though the grain size influenced the plain fatigue, it did not affect the fretting fatigue life. The deleterious effect of fretting in reducing the fatigue life was more pronounced at lower stress levels in both coarse and fine grained material.

Keywords: Fatigue; Fretting fatigue; Grain size; Austenitic stainless steel; Martensitic transformation.

1. Introduction

Fretting fatigue is one of the major failure modes in mechanical systems where service load and mechanical vibrations cause relative sliding movements of very small amplitude between contacting surfaces. Under the influence of fretting, an early initiation and accelerated growth of fatigue cracks occur ultimately leading to failure even at very low stress levels. Examples of fretting fatigue failure can be found in press or shrink fitted joints, riveted joints, bolted joints, wheel-on-axle assemblies, splined shafts, gas turbine parts, wire ropes, machine and structural parts etc.[1] It is reported that up to 50 variables might influence the magnitude and rate of fretting process.[2] Among all, coefficient of friction, magnitude of slip and contact pressure are considered to be the primary set of variables, which can directly affect the fretting process. The remaining are secondary variables such as contact materials, mean stress, surface texture, nature of contact, microstructure, residual stresses, frequency of vibration etc., which can affect the fretting process through the changes they cause in the primary variables. Investigations dealing with the microstructural influence on the fretting fatigue behaviour are found very sparsely in open literature. The present investigation was undertaken to study the effect of grain size on the fretting fatigue behaviour of AISI 304 stainless steel. For reference plain fatigue (with out fretting) studies were also done.

2. Experimental details

The chemical composition (in wt%) of the material used in the present investigation is 0.03 C, 18.29 Cr, 8.91 Ni, 2.0 Mn, 1.0 Si and balance Fe. The material was solution annealed at different temperatures and soaking time periods to get two different grain sizes. The treatment 1050°C / 0.5 h / water quench resulted in a two dimensional mean grain size of 43 μm and the treatment 1200°C / 3.0 h / water quench followed by 1050°C / 0.5 h / water quench produced a grain size of 137 μm. Room temperature tensile properties of the material with two different grain sizes are listed in the Table 1. 7 mm thick specimens of 65 mm gauge length and 10 mm gauge width were used for both plain fatigue and fretting fatigue tests. The gauge portions of all samples were polished with four grades (1/0, 2/0, 3/0 and 4/0) of silicon carbide emery papers and cleaned with acetone. The residual polishing marks were along the length of the specimens.

Table 1 Room temperature tensile properties of AISI 304 stainless steel

Grain size (μm)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
43	221	628	72
137	188	589	76

An experimental facility, with a ring-type load cell and bridge-type fretting pads, which can simulate the fretting fatigue conditions, developed in-house, was used. The details are given elsewhere.[3, 4] Fretting pads were made of the same test material AISI 304 stainless steel. The contact surfaces of the pads were polished with four grades (1/0, 2/0, 3/0 and 4/0) of silicon carbide emery papers and cleaned with acetone prior to each test. Fig. 1(a) shows schematic diagram of the uniaxial fretting fatigue test set up and Fig. 1 (b) shows the fretting fatigue test set up employed in the present study.

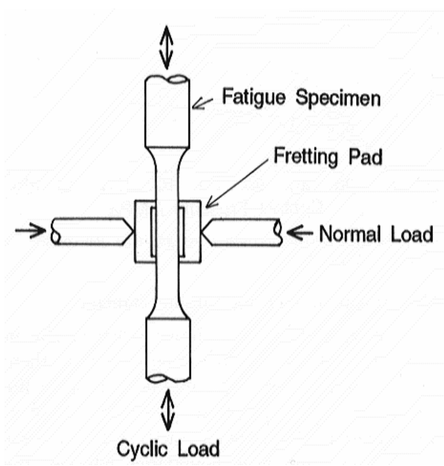

Fig .1(a) Schematic diagram of the uniaxial fretting fatigue test set up

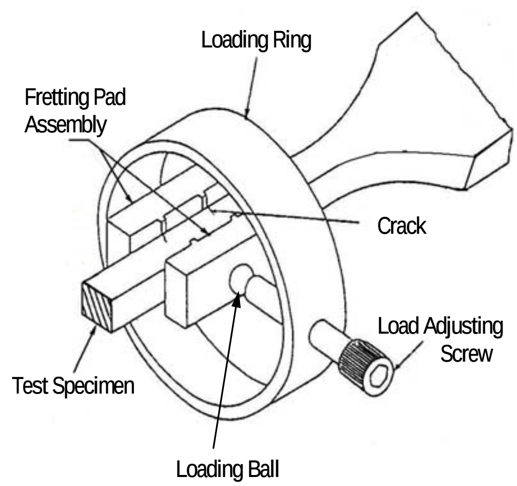

Fig .1(b) Fretting fatigue test set up used in the present study

Normal (contact) load was applied by a proving ring with the help of load adjusting screws. Plain fatigue and fretting fatigue tests were conducted in laboratory air (approximately 60-80% relative humidity) at room temperature on Schenck servo-hydraulic machine with a stress ratio of 0.1 at different cyclic stress amplitudes. For plain fatigue tests the frequency was 30 Hz and for fretting fatigue tests it was 10 Hz. A constant contact pressure of 70 MPa was used in the fretting fatigue tests. During fretting fatigue testing the friction force between the fretting pad and the specimen was measured by bonding strain gauges to the under side of the fretting pads, with the strain gauge grid centered between the pad feet. The contact load applied by the proving ring was monitored and maintained constant throughout the test with the help of a data acquisition system (HBM-Spider8-600 Hz and catman Express 4.0 software). The contact pressure and frictional stress were calculated by dividing the normal load and friction force respectively, by the apparent contact area. The fretting scar regions in the tested specimens were observed at low magnifications and photographs were taken. The roughness profile across the fretting scar was obtained using a perthometer. As the test material AISI 304 austenitic stainless steel was metastable at room temperature, it underwent deformation-induced martensitic transformation during testing. The transformation products were identified using optical microscopy and X-ray diffraction (XRD) employing Fe-K_{α} radiation. The content of magnetic phase α'-martensite was measured using Helmut Fischer ferritescope. A scanning electron microscope was employed to observe the fretting scars and the fracture surfaces of the tested specimens.

3. Results and discussions

3. 1 Plain fatigue tests

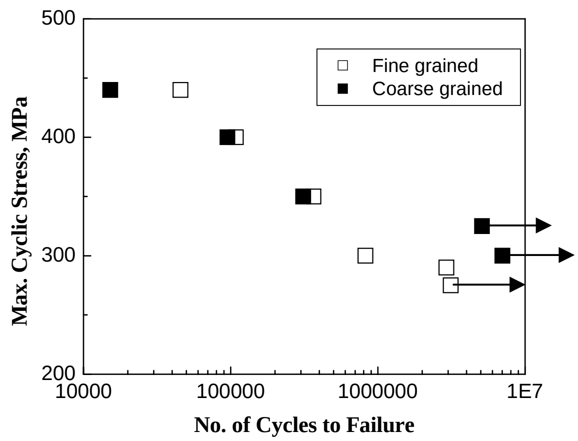

Fig. 2 Effect of grain size on plain fatigue life (arrows indicate non-failure)

Fig. 2 shows the plain fatigue test data for the material with two different grain sizes tested at different maximum cyclic stresses. The material with a grain size of 43 μm is refered to as fine grained material and that with 137 μm is refered to as coarse grained material. As per literature, fine grained materials will have better fatigue properties when compared to coarse grained materials.[5] In the present study this was the case at higher stress levels. However, at lower stress levels, coarse grained material exhibited longer fatigue lives. This may be attributed to the formation of deformation-induced martensite during cyclic loading. Martensite formation reduces crack growth and leads to rapid hardening.[6] The amount of α'-martensite formed was about 5% in coarse grained material and about 1-2% in fine grained material both tested at 250 MPa. The larger amount of martensite in the coarse grained material may be traced to the following fact. As the coarse grained material was developed by solution annealing at a higher temperature (1200°C against 1050°C for fine grained steel), there were more annealing twins present in it. Since twins are one of the preferred sites for martensite nucleation, in the coarse grained material more martensite formed which resulted in greater degree of hardening. At high cyclic stresses formation of martensite was less. This may be because deformation-induced martensite is favoured only after some amout of cumulative strain is induced in the material. This is achieved after certain number of loading cycles, which is dependent on the magnitude of stress. At lower cyclic stresses the cumulative strain may be more, which leads to a higher amount of deformation-induced martensite induced in the material resulting in hardening and improved fatigue life.

Fig. 3 shows the X-ray diffraction results (intensity in counts per second versus angle 2θ, where θ is the Bragg diffraction angle) corresponding to a fine grained specimen before and after fatigue test. The specimen not subjected to deformation contained only austenite (γ). But after deformation the transformation product α'-martensite was identified.

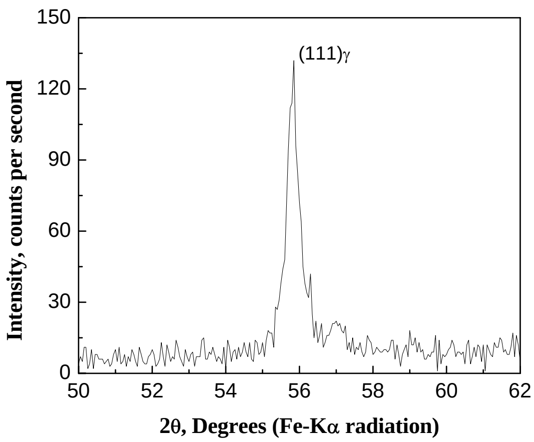

Fig. 3(a)

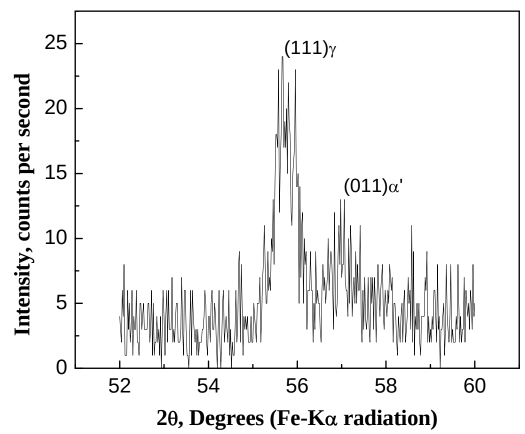

Fig. 3(b)

Fig. 3 X-ray diffraction analysis performed on a fine grained material
(a) before fatigue deformation (b) after fatigue deformation

3.2 Fretting fatigue tests

3.2.1 Effect of fretting on fatigue life

Fig. 4 shows the detrimental effect of fretting on plain fatigue life of both fine grained and coarse grained steel. Fretting had a drastic effect on the plain fatigue life at lower cyclic stress levels. But at higher cyclic stress levels the fretting fatigue life was close to the plain fatigue life. In case of coarse grained material tested at the highest cyclic stress level of 440 MPa fretting fatigue life was longer than the plain fatigue life. The reason behind this is not clear. Some more tests are to be done before any meaningful reason could be found out.

3.2.2 Effect of grain size on fretting fatigue behaviour

Fig. 5 shows the fretting fatigue test data for both fine and coarse grained materials. At all stress levels the data points corresponding to both grain sizes were very close to each other. Though the grain size influenced the plain fatigue life significantly, it did not affect the fretting fatigue life.

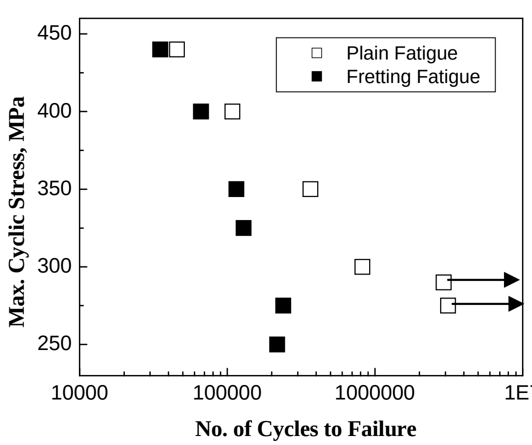

Fig. 4(a)

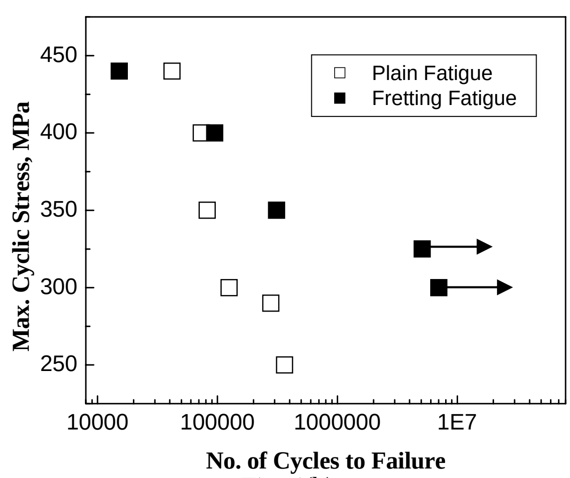

Fig. 4(b)

Fig. 4 Influence of fretting on fatigue life (arrows indicate non-failure)
(a) fine grained material, (b) coarse grained material

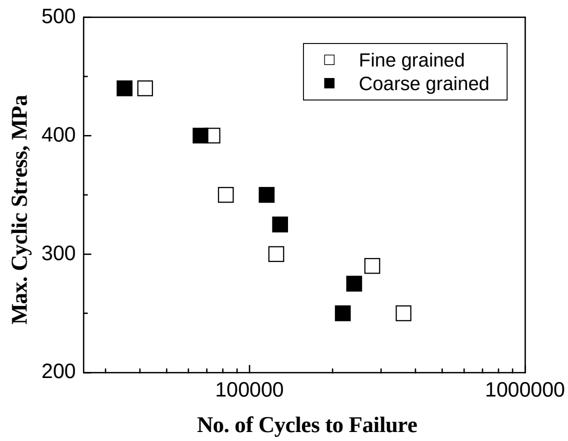

Fig. 5 Fretting fatigue test data for fine and coarse grained material

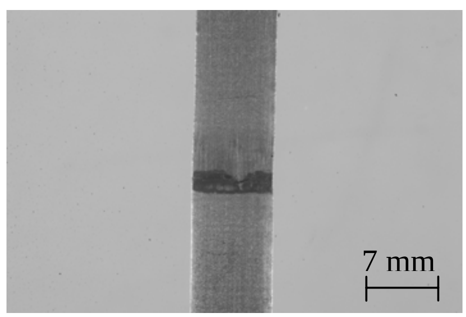

Fig. 6 Appearance of fretting scar in a specimen tested at 440 MPa

Fig. 6 shows the appearance of fretting scar on a fretting fatigue tested specimen.The roughness profiles taken across the fretting scar regions of the specimens are shown in Fig. 7. The middle portion (between the lines) of the profiles corresponds to the fretting scar region and the end portions correspond to unfretted region. It shows that the roughness value for a specimen tested at a higher stress was more than that for a sample tested at a low stress. Also, the surface of the coarse grained material was rougher than that of the fine grained material.

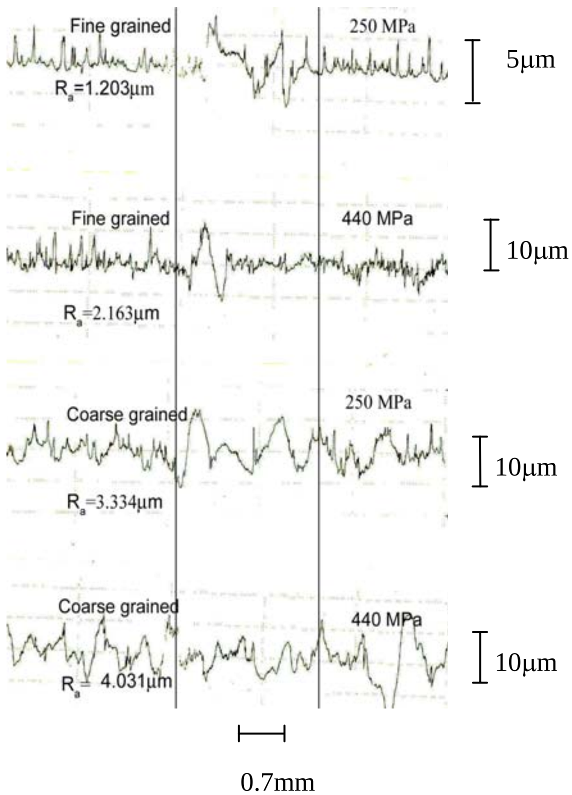

Fig. 7 Roughness profiles taken across fretting scar in specimens tested at two different stress levels

Figs. 8 (a) - (f) show the apparance of fracture surfaces of fretting fatigue tested specimens. Multiple cracks initiated from the contact region (Figs. 8 (a) & (b)). In the region slightly away from the crack initiation sites, no distinct features could be observed. Beyond certain distance distinct striations were observed (Figs. 8 (c) & (d)). Secondary cracking was also seen. The final over load region revealed many dimples (Figs. 8 (e) & (f)).

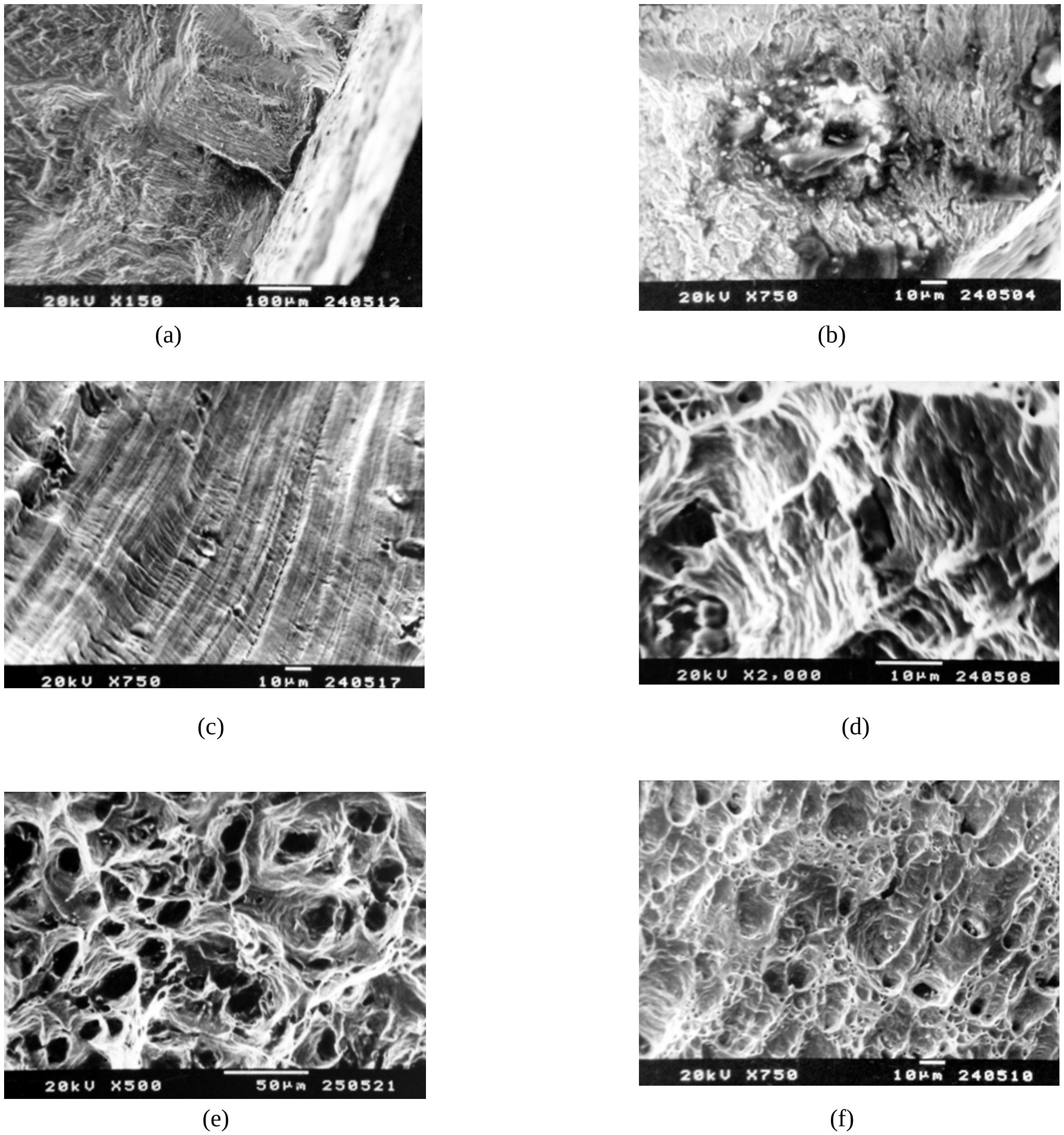

Fig. 8 Appearance of fracture surfaces of tested specimens
(a), (c), (e) – coarse grained material
(b), (d), (f) – fine grained material

4. Conclusions

(a) Grain size had a significant effect on the plain fatigue life of AISI 304 austenitic stainless steel. At higher cyclic stress levels the conventional behaviour was observed, i.e. fine grained material exhibited longer fatigue lives. On the other hand, at lower cyclic stress levels coarse grained material had longer fatigue lives. This was attributed to more amount of martensite formed in the coarse grained material.

(b) Fretting had a drastic effect of reducing the fatigue life in both fine and coarse grained material.

(c) There was no effect of grain size on the fretting fatigue life.

Acknowledgements

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5. References

1. Waterhouse R B, *International Materials Review* **37** (1992) 77.
2. Jan M Dobromirski, *Variables of fretting fatigue process: Are there 50 of them? , in Helimi Attia M and Waterhouse R B (eds) Standardisation of fretting fatigue tests and equipments. ASTM STP 1159, American Society of Testing and Materials,* Philadelphia (1992) 60.
3. Ramakrishna Naidu N K and Ganesh Sundara Raman S, *International Journal of Fatigue* (in press).
4. Ramakrishna Naidu N K, *M.S. Thesis*, IIT Madras (2003).
5. Dieter G E, *Mechanical Metallurgy, SI metric edition*, *McGraw-Hill*, London (1988) p 192.
6. Ganesh Sundara Raman S and Padmanabhan K A, *Materials Science and Technology* 10 (1994) 614.