Roughness Effects on Fretting Fatigue

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Abstract. Fretting is a small oscillatory relative motion between two normal loaded contact surfaces. It may cause fretting fatigue, fretting wear and/or fretting corrosion damage depending on various fretting couples and working conditions. Fretting fatigue usually occurs at partial slip condition, and results in catastrophic failure at the stress levels below the fatigue limit of the material. Many parameters may affect fretting behaviour, including the applied normal load and displacement, material properties, roughness of the contact surfaces, frequency, etc. Since fretting damage is undesirable due to contacting, the effect of rough contact surfaces on fretting damage has been studied by many researchers. Experimental method on this topic is usually focusing on rough surface effects by finishing treatment and random rough surface effects in order to increase fretting fatigue life. However, most of numerical models on roughness are based on random surface. This paper reviewed both experimental and numerical methodology on the rough surface effects on fretting fatigue.

1. Introduction

Fretting is a small oscillatory motion between two contact surfaces by normal load, which may cause fretting fatigue [1-5] and/or fretting wear [6-9] and/or fretting corrosion involving a large number of factors including both material properties and the working environment of fretting couples. Fretting corrosion is the deterioration at the contact interface as a result of corrosion and the micro oscillatory slip. This is a case that chemical reaction rules the extent of the damage during the fretting process, which is not discussed in the paper.

Besides fretting corrosion, fretting wear and fretting fatigue are two main fretting problems. Fretting wear is material removal between two contact surfaces, with oscillated micro relative slip under contact pressure. Given an external alternating load is superimposed on the contact load, fretting fatigue may occur [10]. It results in catastrophic failure at the stress levels below the fatigue limit of the material. Both fretting wear and fretting fatigue often coexist at the same time [11] and come out as competing process. However, generally, fretting wear and fretting fatigue are predominant in gross sliding and partial slip, respectively. The main reason of this is that the micro superficial crack generated in gross sliding condition could be eliminated by the material removal. While due to less wear and high velocity of cracking in partial slip condition, cracks initiated on the contact surface have more opportunity to propagate to the inner of the specimen.

Unlike rolling or reciprocating, usually, fretting happens where the contact surfaces are not supposed to move relatively to each other [12]. This movement is attributed to the deflection of machine components with clamped joints or press fits. Therefore, fretting problems could be found widely in almost all contact conditions due to this small displacement. The nature of fretting involves a large number of factors including both material properties and the working environment of fretting couples, such as the applied normal load and displacement, material properties, roughness of the contact surfaces[13].

As increasing surface roughness is one of key factors enhancing fretting fatigue performance [14], researchers have studied both regular rough surface and random rough surface influence on fretting fatigue by experimental method. Meanwhile, the numerical analysis on random rough surface effects has been conducted. The motivation of present work is to review the research of fretting fatigue related to the roughness effects in both experimental and numerical modelling aspects. This paper is divided 4 parts; after the introduction section, the experimental research of it is reviewed. Then, the numerical methods employed for roughness modelling is presented in section 3. Finally, a conclusion is presented.

2. Roughness effects on fretting fatigue

Surface roughness plays an important role on working performance of fretting couples. By different techniques, the surface presents various topography. By shot peening or laser peening, compressive residual stress and surface roughening are induced. Most of finishing methods, such as turning, grinding, lapping, honing result in irregular roughness pattern, which is described as random distribution. However, using vibration rolling process or laser surface texturing technology, it is possible to achieve regular rough contact surfaces. Therefore, it is worth to study the effects of rough surface by different surface finishing methods.

2.1. Rough surface by shot peening and shot blasting

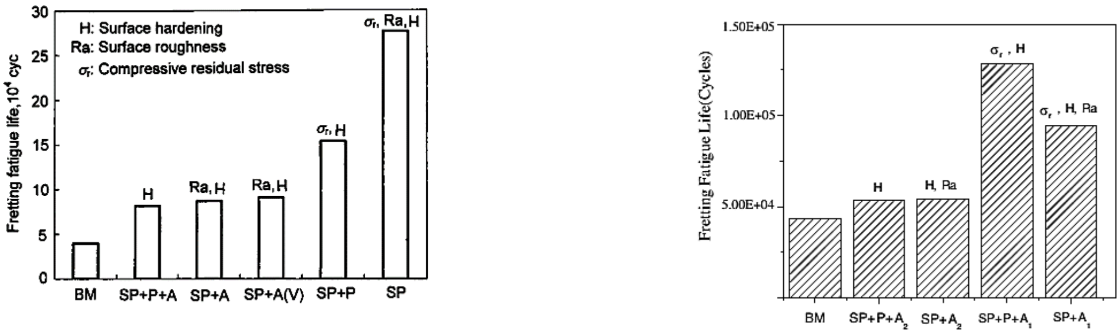
Shot peening is a mechanical surface treatment used to produce a localised plastic flow at component surfaces [15, 16]. This plastic flow not only results in a work hardening and general roughening of surfaces, but also causes a compressive residual stress layer. All these factors may affect the resistance to plain fatigue and fretting fatigue of components.

By studying the experimental work of aluminium alloy with/without shot peening on plain fatigue and fretting fatigue reported in 1984, researchers found that the main reason for improving the fretting fatigue strength is the compressive residual stress induced by shot peening. After reducing the roughness produced by the shot peening, the strength of fretting fatigue decreased [7]. Later on, researches of the same group investigated the effect of the roughening produced by different levels of shot peening on fretting fatigue of an aluminium alloy. After removing the compressive residual stress by heat treatment, the increased peening roughness is progressively less damaging in fretting fatigue [9], as listed in Table 1. This tendency could be explained by Bramhall that the initiation of crack under fretting fatigue area needs a critical volume of material. On rough surfaces the volume of contact regions does not reach this critical volume, hence the fretting fatigue life is increased. In the study of fretting fatigue on aluminium alloy treated by shot peening and laser peening [10], experimental results show that the fatigue life increases with increasing the roughness of contact surfaces due to decreasing the stress intensive factor in mode Ⅱ.

Table 1. Fatigue strengths (in MPa) after removal of residual compressive stress and work hardening[17]

Peening intensity	Roughness peak to valley (μm)	Number of cycles: 10^6		Number of cycles: 10^7	
		Fretting fatigue strength	Reduction (%)	Fretting fatigue strength	Reduction (%)
Unpeened		150		100	
12-16 A	32	75	25	93	46
16-20 A	62	77	23	83	34
8-10 C	98	82	18	50	20

Effects of shot peening on fretting fatigue of Titanium alloy were also studied under both room temperature [11] and elevated temperature (350 ℃ and 500 ℃) [12] conditions. Under the room temperature condition, the compressive residual stress and surface roughness are predominant factors in enhancing fretting fatigue resistance, presented in Figure 1 (a). In contrast to the case of room temperature, the surface roughness plays negative influence on fretting fatigue resistance of Titanium alloy at 350 ℃, shown in Figure 1 (b). This is related to the correlation between compressive residual stress and shot peening-induced surface morphology changes. They are different at elevated temperature compared to room temperature.



(a) (b)

Figure 1. Fretting fatigue lives with different surface treatment,(a) under room temperature [18], (b) under 350 ℃ [19]

Shot blasting is a treatment for preparing the surface to be coated. By shot blasting, this surface is roughened to provide a strong mechanical bond between coating and the substrate. The objectives of shot peening and shot blasting are different. Shot peening is intentionally applied for improving the fatigue resistance. However, the shot blasting is a technical treatment before coating. In the experimental work on Al–Mg–Si alloy AA6061 as presented in [20], it is found that shot blasting significantly increased fretting fatigue life by a factor 2.4 at a maximum cyclic stress of 169 MPa, but at higher stress levels shot blasting slightly reduced the fretting fatigue life.

2.2. Regular rough surface

The vibration rolling process is a finishing technique that produces a regular surface microgrooves pattern. As shown in Figure 2, turning and polishing, which are conventional finishing methods, generate irregular pattern on the surface while the regular patterns are produced by vibrorolling, though the groove depths are equal by these three different methods. Researchers [21] of the St Petersburg Precision Mechanics and Optics University found that regular grooves help remove wear debris from the contact surface and distribute stress and plastic deformation, effectively reducing the fretting damage.

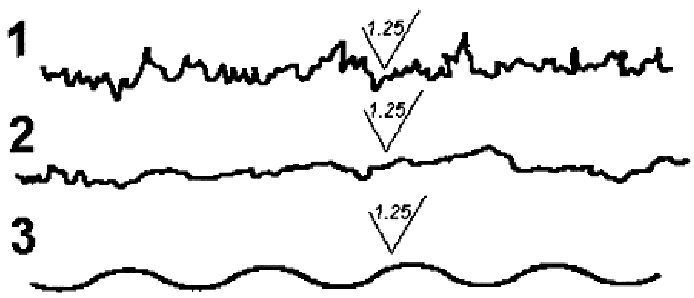


Figure 2. Topography of surfaces, finished by different methods: (1) turning, (2) polishing, (3) vibrorolling.[21]

The regular micropore is another type of regular surface roughness pattern, as shown in Figure 3. During fretting, the wear debris may escape into these micropores. In the study of fretting fatigue with cylinder on beam subjected the fatigue load contact [10], micropores of the contact surface are produced by the laser surface texturing. It is found that effects of micropores of component surface play different roles on fretting fatigue depending on if this component is subjected the fatigue load. As listed in Table 2, the fretting fatigue life of the beam with deeper regular micropores is reduced due to the generation of the stress concentration induced by the micropores on the beam surface. In contrast, the appearance of micropores on the cylinder surface has beneficial influence on the fretting fatigue life, which is twice compared to the case without textured surface. This is because that the wear debris moves into these micropores and thus reduces the relative slip between contact surfaces.

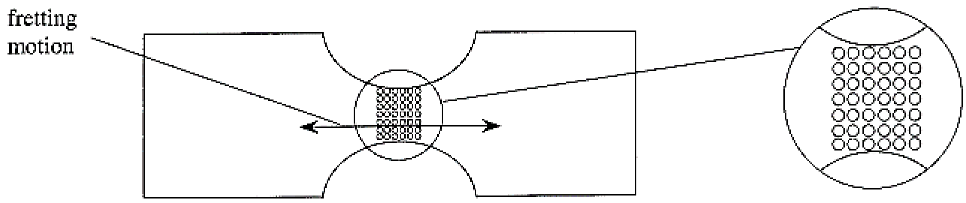


Figure 3. Micropores on the beam for fretting experiments [10]

Table 2. Mean life in the fretting fatigue experiments [10]

Experiment type	Pore depth (μm)	Mean fretting fatigue life (×10^5 cycles)
No textured	0.0	5.18
Textured beam	5.3	4.67
Textured beam	2.6	7.82
Textured cylinder	5.9	9.34
Textured cylinder	31.9	9.72

2.3. *Random rough surface*

In industry applications, most surfaces of parts are finished by turning, grinding, lapping, honing, etc. The surface microgrooves distribute vary in shape, size and relative location due to the asperities and waviness. In this case, many roughness parameters are created for describing the roughness of the surface. In the study of fretting fatigue, usually the average roughness *Ra* and the maximum height of the profile *Rt* are used to describe the roughness of the contact surface.

In the investigation of fretting fatigue on Titanium ally in low and high cycle fatigue life regions [22], researcher found that the fretting fatigue life with smoother surface (Ra = 13.2~32.2 nm) is longer than the case with rougher surface (Ra = 120~140 nm) in both low cycle and high cycle fatigue life conditions, displayed in Figure 4.

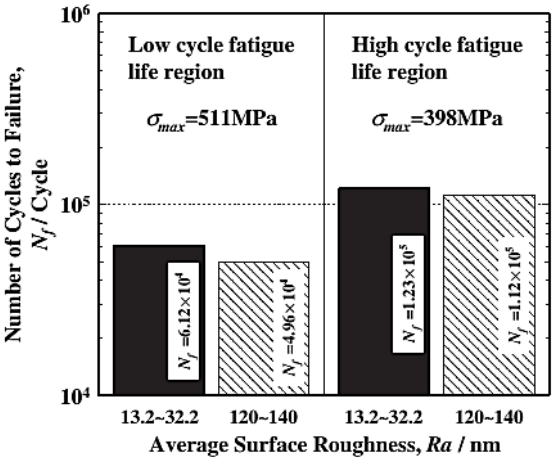
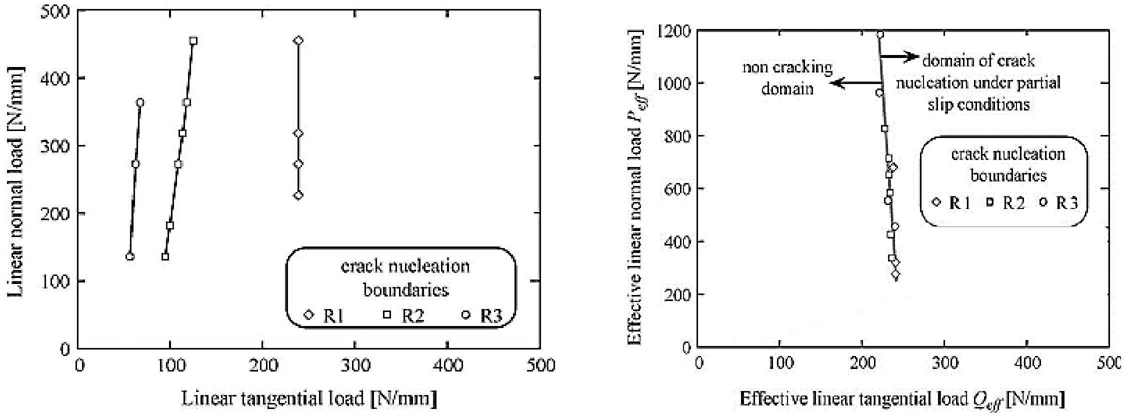


Figure 4. Fretting fatigue lives of fretting couples with different rough surfaces [22]

The roughness effects on fretting fatigue of Aluminium alloy also have been studied [23], especially on the process of the crack nucleation. By investigating the fretting fatigue results of three different rough surfaces shown in Table 3, researchers found that a smoother surface leads to a higher tangential load for the crack initiation presented as Figure 5 (a). By introducing effective linear loads, which is calculated by the effective contact length, it reveals that the crack initiation of 2024 Aluminium alloy depends on the local stress status determined by the real contact area between rough surfaces, shown as Figure 5 (b).

Table 3. Ra and Rt of different surfaces [23]

	R1	R2	R3
Ra (μm)	0.11	0.6	0.75
Rt (μm)	1.05	3.1	3.15



(a) (b)

Figure 5. The relation between the crack nucleation and the linear loads/ effective linear loads with three different roughness [23], (a) linear loads, (b) effective linear loads

3. Numerical modelling on roughness effects on fretting fatigue

The research on modelling of fretting fatigue considering roughness effects is very limited. Kasarekar [24, 25] proposed a numerical modelling method that investigate the evolution of fretting fatigue life of Hertzian rough contacting bodies in fretting wear. One of the most used numerical modelling technique is Finite Element Analysis, which has been widely used in the literature for many engineering applications [26-39]. Effect of surface roughness parameters, i.e. root mean square, skewness and orientation is evaluated. The results show that the location of crack initiation changes from trailing edge to the stick-slip zone interface during fretting wear process according to the crack initiation parameter. Increasing the roughness of contact surfaces reduces the fretting fatigue life. Beheshti [40] introduced a robust approach for prediction of the surface tractions in rough contact under partial slip condition. This numerical model is applied to study the fretting fatigue crack initiation. Results also indicate that higher surface roughness leads to higher risk of crack initiation.

4. CONCLUSION

The research on effects of roughness of contact surfaces on fretting fatigue has been reviewed. Shot peening and laser peening are two finishing treatment used for improving the fretting fatigue resistance. This is because that they could generate compressive residual stress approaching the contact surface and roughen surface. Effects of roughness on fretting fatigue are contradictory. For the shot peening or laser peening experiments, rougher surface induces higher fretting fatigue resistance when removing the compressive residual stress. Introducing regular rough surface also improve the anti-fretting fatigue performance. However, on the random rough surface research, it is found that rougher surface has negative effect on the fretting fatigue life. The numerical study on the roughness effects on fretting fatigue is very limited. The reported results show that the higher roughness of surface reduce the fretting fatigue life.

References

[1] Martínez JC, Vanegas Useche LV and Wahab MA 2017 *International Journal of Fatigue* **100, Part 1** 32-49
[2] Kumar D, Biswas R, Poh LH and Abdel Wahab M 2017 *Tribology International* **109** 124-132
[3] Bhatti NA and Abdel Wahab M 2017 *Tribology International* **109** 552-562
[4] Resende Pereira KdF, Bordas S, Tomar S, Trobec R, Depolli M, Kosec G and Abdel Wahab M 2016 *Materials* **9** 639; doi:610.3390/ma9080639
[5] Ferjaoui A, Yue T, Abdel Wahab M and Hojjati-Talemi R 2015 *International Journal of Fatigue* **73** 66-76
[6] Yue T and Abdel Wahab M 2017 *Tribology International* **107** 274-282
[7] Pereira K, Yue T and Abdel Wahab M 2017 *Tribology International* **110** 222-231
[8] Yue T and Abdel Wahab M 2016 *Materials* **9** 597; doi:510.3390/ma9070597
[9] Yue T and Abdel Wahab M 2014 *Wear* **321** 53-63
[10] Volchok A, Halperin G and Etsion I 2002 *Wear* **253**(3–4) 509-515
[11] Vincent L, Berthier Y, Dubourg MC and Godet M 1992 *Wear* **153**(1) 135-148
[12] Neale MJ and Gee M. Chapter 2 - Industrial wear problems. A Guide to Wear Problems and Testing for Industry. Suffolk, UK: William Andrew Publishing; 2001. p. 3-III.
[13] Braunovic M 2009 *IEICE Transactions on Electronics* **92**(8) 982-991
[14] Fu Y, Wei J and Batchelor AW 2000 *Journal of Materials Processing Technology* **99**(1–3) 231-245
[15] Leadbeater G, Noble B and Waterhouse R 1984 Proc. Int. Conf. on Fracture ed editors (New Delhi) p. 2125–2132
[16] Liu KK and Hill MR 2009 *Tribology International* **42**(9) 1250-1262
[17] Waterhouse RB and Trowsdale AJ 1992 *Journal of Physics D: Applied Physics* **25**(1A) A236
[18] He DLJ 2001 *Acta Metallrugica Sinica* **37**(2) 5

[19] Zhang X and Liu D 2009 *International Journal of Fatigue* **31**(5) 889-893
[20] Naidu NKR and Raman SGS 2005 *International Journal of Fatigue* **27**(3) 323-331
[21] Bulatov VP, Krasny VA and Schneider YG 1997 *Wear* **208**(1–2) 132-137
[22] Takeda J, Niinomi M, Akahori T and Gunawarman 2004 *MATERIALS TRANSACTIONS* **45**(5) 1586-1593
[23] Proudhon H, Fouvry S and Buffière JY 2005 *International Journal of Fatigue* **27**(5) 569-579
[24] Kasarekar AT, Bolander NW, Sadeghi F and Tseregounis S 2007 *International Journal of Mechanical Sciences* **49**(6) 690-703
[25] Kasarekar AT, Sadeghi F and Tseregounis S 2008 *Wear* **264**(7–8) 719-730
[26] X. Nguyen H, N. Nguyen T, Abdel Wahab M, Bordas SPA, Nguyen-Xuan H and P. Voa T 2017 *Computer Methods in Applied Mechanics and Engineering* **313** 904-940
[27] Tran Vinh L, Lee J, Nguyen-Van H, Nguyen-Xuan H and Abdel Wahab M 2015 *International Journal of Non-Linear Mechanics* **72** 42-52
[28] Tran LV, Phung-Van P, Lee J, Wahab MA and Nguyen-Xuan H 2016 *Composite Structures* **140** 655-667
[29] Thai CH, Ferreira AJM, Abdel Wahab M and Nguyen-Xuan H 2016 *Acta Mechanica* **227**(5) 1225-1250
[30] Thai C, Zenkour AM, Abdel Wahab M and Nguyen-Xuan H 2016 *Composite Structures* **139** 77-95
[31] Phung-Van P, Tran LV, Ferreira AJM, Nguyen-Xuan H and Abdel-Wahab M 2016 *Nonlinear Dynamics* 1-16; doi:10.1007/s11071-11016-13085-11076
[32] Phung Van P, Nguyen LB, Tran Vinh L, Dinh TD, Thai CH, Bordas SPA, Abdel Wahab M and Nguyen-Xuan H 2015 *International Journal of Non-Linear Mechanics* **76** 190-202
[33] Phung Van P, De Lorenzis L, Thai CH, Abdel Wahab M and Nguyen-Xuan H 2015 *Computational Materials Science* **96** 495-505
[34] Phung Van P, Abdel Wahab M, Liew KM, Bordas SPA and Nguyen-Xuan H 2015 *Composite Structures* **123** 137-149
[35] Noda N-A, Chen X, Sano Y, Wahab MA, Maruyama H, Fujisawa R and Takase Y 2016 *MATERIALS & DESIGN* **96** 476-489
[36] Tran Vinh L, Lee J, Ly HA, Abdel Wahab M and Nguyen-Xuan H 2015 *International Journal of Mechanical Sciences* **96-97** 65-78
[37] Junyan Ni and Wahab MA 2017 *Computers & Structures* **186** 35–49
[38] Phung-Van P, Qui LX, Nguyen-Xuan H and Wahab MA 2017 *Composite Structures* **166** 120–135
[39] Phung-Van P, Ferreira AJM, Nguyen-Xuan H and Abdel Wahab M 2017 *Composites Part B: Engineering* **118** 125-134
[40] Beheshti A, Aghdam AB and Khonsari MM 2013 *International Journal of Fatigue* **56** 75-85