Discussion on ~~"Effect~~ "Effect of out-of-phase loading on fretting fatigue response of Al7075-T6 under cyclic normal loading using a new testing apparatus" by F. Abbasi and G.H. Majzoobi

M. Ciavarella

mciava@poliba.it

Politecnico di ~~BARI.~~ BARI, Center of Excellence in Computational ~~Mechanics.~~ Mechanics, Viale Gentile 182, 70126 ~~Bari.~~ Bari, Italy

Abstract

Fretting fatigue has been studied mainly with constant normal load. Abbasi and Majzoobi ~~[1]~~ (2017) suggest an new testing method where contact pressure can be independently varied during the test. The authors compare the case of constant normal load, with that of in phase or 90° and 180° degrees out-of-phase loads, but at the same frequency. However, the results are not obvious to interpret, and it is hoped that a reply from the authors and a discussion could lead to some progress. In particular, contact mechanics (and even the authors' own numerical simulations) seem in contrast with some experiments. Also, the case of constant normal load is found to be the *least* damaging despite less frictional force is developed which seems to imply an oxidation phenomenon which depends on greater exposure to air, but the time of tests seems similar. If these surprising effects are confirmed, this varying normal load effect calls for some new models in fretting. Or there is something wrong in the experiments?

Keywords: ~~Fretting-Fatigue~~Fretting-fatigue; Fretting wear; Wear; Contact problems; Tribology

1 Introduction

Abbasi and Majzoobi [1] have recently presented some work related to the effect of out-of-phase loading on fretting fatigue response of Al7075-T6 under cyclic normal loading using a new testing apparatus. The vast majority of fretting experiments assumes that the normal contact load is constant, because this is certainly considered to be simpler to realize in experiments and much simpler to analyze in terms of stress field induced. For a review of experimental rigs, and of much of the progress and understanding, see the very good review of Nowell et ~~al~~ al. [2], where a series of references is collected. Many authors have recently concentrated on the ~~"fatigue~~ "fatigue aspect" especially to capture the fracture mechanics size dependence on the contact area, which was recognized very neatly by the MIT group of Suresh in the so-called ~~"crack~~ "crack analogue" (CA) model of fretting [3] which essentially avoids all numerical calculations, simplifies the shear stress distribution due to the contact problem (which is correct anyway for large friction coefficient), and also defines a mode I and mode II SIF again simplifying the geometry as square ended. However, similarly, many contributions from Oxford, Purdue and others (see again [2]) used essentially concepts of fatigue from notches and cracks perhaps using Hertzian pads in order to resolve the details of the stress field (and also, as a side effect, solve alignments problems). The shape of the contacting bodies during tangential oscillatory loading was in the early times important in order to know the detailed solution of the stress field induced in the so called Cattaneo problem, although this was later on shown a solution easily generalized to almost any geometry with the ~~"Ciavarella-Jaeger"~~ "Ciavarella-Jaeger" theorem [4]. The original CA model may seem quite arbitrary for geometries which have no sharp corners, but the reason why this works is that Mode I stress field is constant (and is actually compressive, so it has no strict equivalent in standard Fatigue as it would simply close the crack), and that the distribution of shear stresses is often at the highest loads very close to the singular distribution of the fully stuck flat punch. In fatigue, it is well known that notches behave ~~"crack-like"~~ "crack-like" if they are not too large and then like ~~"blunt~~ "blunt notches", so that a unified approximate treatment reveals that it is the stress at a given ~~"critical~~ "critical distance" ahead of the crack or notch which matters, and this eliminates many details [5–7].

However, another, perhaps even older school of thought, attributes to fretting damage a crucial role, and has studied fretting wear and fretting fatigue with ~~"fretting~~ "fretting maps", introduced by Vingsbo and Soderberg [8] in a largely cited ~~paper — diagrams~~ paper—diagrams showing regime boundaries representing critical values for the transition from one regime to another. They observed, also reviewing the literature about both fretting wear and fretting fatigue, that

1. at low amplitudes of displacement, a ~~"stick~~ "stick regime" is found with no crack formation. This is also partly in contrast with the classical Cattaneo-Mindlin-Ciavarella-Jaeger [4] picture for which slip should immediately initiate at the edges of contact for arbitrarily small tangential force;
2. at higher amplitudes, a partial slip regime with an annular slip region appears, in which extensive crack formation is observed (crack lengths in metals are ~~10 - 40~~ 10-40 microns. Strongly reduced fatigue life).
3. gross slip regime. Severe surface damage by wear, assisted by oxidation. Limited crack formation. Fretting wear rather than fretting fatigue. There is a competing mechanism of crack formation and crack removal due to wear, as observed for

example in rail-wheel rolling contact [9,10], and was proposed by Waterhouse [11].

4. reciprocating sliding regime ~~(“Sliding~~ (“Sliding wear”). Wear mechanisms and wear rates become similar to those of unidirectional sliding.

In the most famous map, see Fig. 1, it is seen that the most detrimental regime in terms of fatigue life is an intermediate range for fretting amplitude displacement of the order of $20\,\mu m$. This map has been later found to give an erroneous finding [12], in that slip in the contact area show is not the same as the applied remote displacement, and the strong dependence of wear on fretting amplitude in gross sliding was questioned.

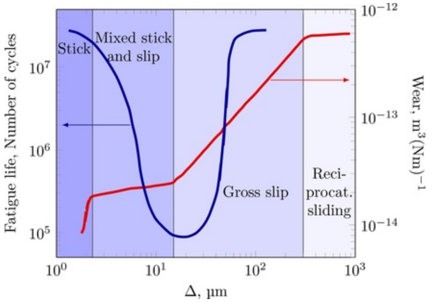

Fig. 1 The well known fretting map introduced by Vingsbo and Soderberg [8] showing regime boundaries: in mixed stick-slip, prevalance of fretting-fatigue, in gross slip, prevalence of fretting wear.

Now, below this amplitude displacement of the order of $20\,\mu m$ probably the frictional force is much smaller (in these experiments, the frictional force is a reaction to an imposed displacement) and therefore we could expect that fretting life increases. At higher values, instead, life increases only when full slip occurs: but the correlation with the increase of the wear rate should be reconsidered in view of the Pearson & Shipway findings [12]. The beneficial effect of wear is important for applications like turbine joints attachments, where in general conditions are closer to partial slip than to full slip regime, provided of course wear is tolerated and replacement of parts is done in regular maintenance intervals.

More recently, Madge et al. [13] simulated cylinder on plane fretting fatigue conditions using FEM, taking into account wear (Archard law) and accumulation of fatigue damage with initiation parameters and Palmgren-Miner damage rules, and similar approaches have been followed also in other works [14]. The argument that increasing fatigue life in the gross sliding regime is explained by combined action of ’crack embryo wipe-out mechanism’ and gradual increase in contact area alleviating overall fatigue load has been confirmed.

Huq et al. [15,16] Hojjati-Talemi et ~~al~~ al. [17] Xin et al.[18] examined the effect of cyclic normal load on fretting fatigue lifetime, and found that the presence of cyclic normal loading condition reduces fatigue lifetime drastically, and this is confirmed by the paper under discussion [1]. However, it is unclear if this can be attributed to the decrease in crack initiation lifetime which is controlled by frictional and contact stresses. Depending on how the cyclic normal load occurs, slip may occur or not occur, and perhaps [1] shows an interesting new feature, by changing the phase with respect to the tangential load. Hattori et al. [20] present simple fretting fatigue limit estimation method based on the assumption that in the final stage of wear process the contact pressure distributions near contact edges converge to a uniform distribution.

The scope of the present discussion is to raise three points, listed in the abstract, hoping that some of them could be also answered by the authors of [1]:-

(1) when load is varied in phase with the axial stresses in the specimen, contact mechanics [21] and even the authors own simulations would predict that no slip should be obtained, whereas apparently larger slip is found with respect to the constant normal load. How can this be explained?

(2) that the case of constant normal load is found to be the *least* damaging despite less frictional force is developed (the ~~“full~~ “full sliding limit” is also time-varying so we don’t reach the maximum normal load in phase) is also curious. It has been found in another paper by the same authors, just accepted [22] that frequency of normal load has a dramatic influence, and at large frequencies the effect disappears. However, the experiments were conducted using the same far field axial load frequency of ~~10Hz.~~ 10 Hz. So the time of the test is mainly given by the number of cycles of the axial load, and the frequency of normal load does not seem to change the total exposure time.

(3) this varying normal load effect calls for some new models in fretting, as we briefly review. Indeed, ~~“crack~~ “crack and notch” analogues which do not consider the tribological effects of wear, and the more recent models which either consider wear only as a change of the contact geometry, or attempt also to find the damage in the material with initiation models while geometry is changing due to wear – not a real competing effects of cracks initiated and removed.

2 Contact mechanics under varying normal load

As [1] makes use of independent control of the normal force P closing the contact, and the axial stress in the specimen σ_b (which in turn is resisted by tangential forces Q in bridge pad specimen), we can imagine this corresponds to a prescribed loading cycle involving normal tangential and bulk stress. The most general form will be

$$Q(t) = Q_m + Q_a F_Q(t) \quad \textbf{(1)}$$

$$P(t) = P_m + P_a F_P(t) \quad \textbf{(2)}$$

$$\sigma_b(t) = \sigma_{bm} + \sigma_{ba} F_\sigma(t) \quad \textbf{(3)}$$

where $P > 0$ at all times since otherwise we lose contact, and $F_i(t)$ are periodic functions. Subscripts ~~”a”~~ “a” refer to amplitude of the respective component of stress or load, and ~~”m”~~ “m” refers to the mean values. One case of interest is when the periodic functions are all in phase, and in particular we can consider an harmonic variation. This leads in the plane P,Q to a simple line (we consider here a ~~”pulsating”~~ “pulsating” load $Q_m = Q_a$ and $\sigma_{ba} = \sigma_{bm}$, as indicated in Fig. 2).

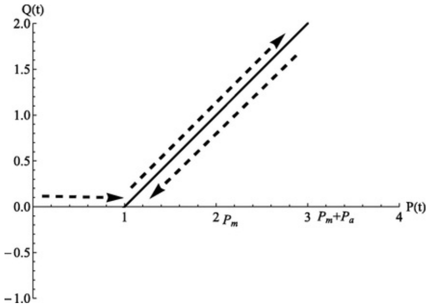

Fig. 2 Pulsating (in phase) loading cycle after an initial state of pure normal loading, in the example $P_m = 2, Q_m = Q_a = P_a = 1$ (arbitrary units). The inclination Q_a/P_a of the line is less than friction coefficient (with bulk stress, a more precise condition can be written). In fact, the authors of [1] consider a load ratio $R = 0$ so that $Q_m = P_m = \sigma_{bm} = 0$.

As the case of constant normal load does not lead to full sliding, for the same imposed maximum bulk stress there is no reason to think that there will be full sliding under in-phase loading, and hence the line is inclined less than friction coefficient. Assuming full stick implies that (see also [21]), the shear traction distribution $q(x)$ will be

$$\frac{\partial q(x)}{\partial P} = \frac{1}{\pi\sqrt{a(P)^2 - x^2}}\left(\frac{\partial Q}{\partial P} + \frac{\pi}{4}\frac{\partial \sigma_b}{\partial P}x\right). \quad \textbf{(4)}$$

This implies obviously that if $\frac{\partial Q}{\partial P}$ and $\frac{\partial \sigma_b}{\partial P}$ are constant, and if as in our in-phase loading case, then integrating the equation above leads to bounded solutions: the term involving the tangential load is exactly proportional to the increase of the pressure distribution in any finite interval, and this leads, for

$$\frac{|Q|}{P} + \frac{\pi}{4}\frac{\sigma_b a}{P} < f \quad \textbf{(5)}$$

to a full stick solution, where f is friction coefficient. This is confirmed by Fig. 20 of [1] which shows, presumably, numerical solution of the problem, where the case of proportional in phase loading finds negligible slip. However, this seems in contrast with Fig. 18 where optical microscopy pictures of contact region seem to indicate more important wear scars and more extensive slip zones for this case, rather than the case of normal load. This raise the first question, which hopefully could be answered by the authors of [1]. How this can be explained?

3 Fatigue life

Despite in theory the case of constant normal load has small slip areas, this is found to be the *least* damaging in experiments as in Fig. 15 of [1], while the in-phase loading is found to be the *most* damaging. The authors appeal to the Vingsbo & Söderberg map but their findings are instead quite in contrast with the classical maps; they also point to a possible effect of air exposure in the case of varying contact area, but it is hard to believe this could have such a profound influence, or anyway it is not clear why this effect should disappear when frequency of normal load alone (and not of bulk stresses) is increased as in [22].

When loads are out-of-phase, the ~~”full~~ “full sliding limit” is also time-varying and in particular when axial stress is at its maximum, normal force is not, so that the tangential force we can develop will be much smaller than the case of constant normal force (which in turn should be the same of the in-phase loading). It is a pity we don’t have actual measurements of the frictional force, which would also shed some ~~ligth~~ light about the possible increase of friction coefficient, which may depend on the loading regime.

With less frictional force, it is not surprising that life is greater than for proportional loading, especially as we probably enter in a regime of higher wear rate (again, it would be nice to have estimates with respect to Vingsbo & Söderberg maps, or, much better, the modern ones with accurate measurements of local displacements), but why should life be shorter than in the case of constant normal load — we have both smaller friction force, and greater wear!

A tentative explanation advanced by the same authors in a recent paper which we discovered in press [22] is that the normal load frequency of the cyclic load was found to be a crucial factor. In [22], the experiments were limited to in-phase loading, and for a frequency of $f = 1$ Hz, fatigue life decreased by 52% in the high cycle fatigue regime whereas of 28% in the low cycle fatigue regime (see Fig. 3). However, for frequency of ~~80 Hz,~~ 80 Hz, the fretting fatigue life converged to its corresponding life under constant normal load condition. In other words, in Fig. 3 fatigue curves move to the ~~rigth~~ right when normal load frequency is increased.

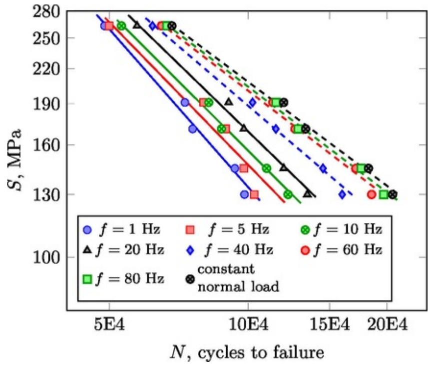

Fig. 3 Adapted from [22] S-N fatigue curves obtained for (in phase) loading, but different normal load frequency, while far field stress $S = \sigma_b$ (and hence tangential) loading is at 10 Hz.

After examination with optical and scanning electron microscopy (SEM) of the fracture surface and the fretting area of the specimens, it was concluded that wider slip regions result compared to constant normal loading, severe delamination, and higher oxidation rate due to the normal load release at each cycle.

We cannot easily apply contact mechanics argument to the case of different frequency between normal load and the other loads, However, fatigue life is greatly reduced even for frequency of ~~10Hz,~~ 10 Hz, which is the frequency of the far field axial load (the case reported in [1]), for which we have made the discussion earlier, with apparently solid contact mechanics arguments, which do not depend much on geometry and therefore should not be invalidated by possible progress of wear either. Our enigma remains as to why slip areas should increase, and why slip should occur at all!

In the more general frequency case, the frequency of normal load does not seem to change the total exposure time much, so although we cannot apply our simple contact mechanics arguments to the general case of different frequencies, it is a ~~mistery~~ mystery what happens at the interface. What is missing, chemistry of wear, or perhaps the change of friction coefficient? Or there is something wrong ~~occuring~~ occurring in the testing rig? These experiments do not permit clarification.

One possibility to perhaps interpret the findings is that the condition for full sliding was really overpassed, and it would be interesting to get an answer from the authors on this. Clearly, this would complicate the interpretation of the problem significantly, since the cycle of stress at each individual point depends not only on loads, but also on absolute values of imposed displacements. Already for a single DOF, the possible regimes of stick slip are quite complicated [25,26]. Further, wear may change the geometry and this can be taken into account with simplicity only in simple problems [27]. More complicated friction laws can give rise to complex non-linear dynamic effects [28]. The role of a different static and dynamic friction coefficient also induces an energetic interpretation of friction [29,30]. Finally, if loading is not imposed along the interface, tilting effects may be important [31].

4 Conclusions

This investigation [1] has the merit to have introduced finally a change of normal load in fretting experiments with the clever idea to change the phase between normal and tangential (and far field) loads. For perhaps too long time tests have been conducted, for simplicity, under constant normal load. A large literature exists on very detailed investigations of stress field induced by the contact, and in principle recently investigations of the contact mechanics under varying normal load has made progress [21,23,24]. However, although very simple accounts of stress concentration have had significant success [3–7] under constant normal load, the fretting fatigue experiments of [1] are not easy to explain. The growth of friction coefficient during cycling has remained very empirical and since it is well known to possibly increase largely, we do not know in details if this changes with changing normal load. The interplay of fretting fatigue and wear has been explored tentatively only recently with quite elaborate models, but largely remains unexplored under varying normal loads. Hence, the investigation [1] has the merit to pose new interesting questions. But until some clarification occurs on these effects, it is very strange that slip occurred under proportional loading at all, and it would seem contact mechanics is completely unable to explain this basic point, which then is responsible for all the conclusions.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.engfracmech.2018.01.031.

References

[1] Abbasi F, Majzoobi GH. Effect of out-of-phase loading on fretting fatigue response of Al7075-T6 under cyclic normal loading using a new testing apparatus. Eng Fract Mech; 2017.https://doi.org/10.1016/j.engfracmech.2017.08.010 Available online 7 August 2017 in press, Corrected Proof.

[2] D. Nowell, D. Dini and D.A. Hills, Recent developments in the understanding of fretting fatigue, *Eng Fract Mech* **73** (2), 2006, 207–222.

[3] A.E. Giannakopoulos, T.C. Lindley and S. Suresh, Aspects of equivalence between contact mechanics and fracture mechanics: theoretical connections and a life-prediction methodology for fretting-fatigue, *Acta Mater* **4** (9), 1998, 2955–2968.

[4] M. Ciavarella, The generalized Cattaneo partial slip plane contact problem. I—Theory, *Int J Solids Struct* **35** (18), 1998, 2349–2362.

[5] M. Ciavarella and G. Macina, A note on the crack analogue model for fretting fatigue, *Int J Solids Struct* **40** (4), 2003, 807–825.

[6] M. Ciavarella, A ‘crack-like’notch analogue for a safe-life fretting fatigue design methodology, *Fatigue Fract Eng Mater Struct* **26** (12), 2003, 1159–1170.

[7] M. Ciavarella, Some observations on the CLNA model in fretting fatigue, *Tribol Int* **39** (10), 2006, 1142–1148.

[8] O. Vingsbo and S. Söderberg, On fretting maps, *Wear* **126** (2), 1988, 131–147.

[9] G. Donzella, M. Faccoli, A. Ghidini, A. Mazzu and R. Roberti, The competitive role of wear and RCF in a rail steel, *Eng Fract Mech* **72** (2), 2005, 287–308.

[10] G. Donzella, A. Mazzù and C. Petrogalli, Competition between wear and rolling contact fatigue at the wheel—rail interface: some experimental evidence on rail steel, *Proc Inst Mech Eng Part F: J Rail Rapid Transit* **223** (1), 2009, 31–44.

[11] R.B. Waterhouse, Fretting fatigue, 1981, Applied Science Publishers.

[12] S.R. Pearson and P.H. Shipway, Is the wear coefficient dependent upon slip amplitude in fretting? Vingsbo and Söderberg revisited, *Wear* **330**, 2015, 93–102.

[13] J.J. Madge, S.B. Leen, I.R. McColl and P.H. Shipway, Contact evolution based prediction of fretting fatigue life: Effect of slip amplitude, *Wear* **262** (9), 2007, 1159–1170.

[14] P. Arnaud, S. Fouvry and S. Garcin, Wear rate impact on Ti-6Al-4V fretting crack risk: experimental and numerical comparison between cylinder/plane and punch/plane contact geometries, *Tribol Int* **108**, 2017, 32–47.

[15] M.Z. Huq, C. Butaye and J.P. Celis, An innovative system for laboratory fretting wear testing under oscillating normal force, *J Mater Res* **15** (7), 2000, 1591–1599.

[16] M.Z. Huq and J. Celis, Fretting fatigue in alumina tested under oscillating normal load, *J Am Ceramic Soc* **85**, 2002, 986–988.

[17] R. Hojjati-Talemi, M.A. Wahab and D.P. Baets, Finite element simulation of phase difference effects on fretting fatigue crack nucleation behaviour, *Proc IMechE Part J: J Eng Tribol* **228** (4), 2014, 470–479.

[18] L. Xin, Y. Jianwei, L. Meihong and Z. Zhengxing, An investigation on fretting fatigue mechanism under complex cyclic loading conditions, *Int J Fatigue* **88**, 2016, 227–235.

[20] T. Hattori, K. Yamashita and Y. Yamashita, Simple estimation method of fretting fatigue limit considering wear process, *Tribol Int* **108**, 2017, 69–74.

[21] D.A. Hills, M. Davies and J.R. Barber, An incremental formulation for half-plane contact problems subject to varying normal load, shear, and tension, *J Strain Anal Eng Des* **46** (6), 2011, 436–443.

[22] Majzoobi GH, Abbasi, F. An investigation into the effect of normal load frequency on fretting fatigue behavior of Al7075-T6. Tribol Trans; 2017, (just-accepted), 00-00.

doi:https://doi.org/10.1080/10402004.2017.1371366.

[23] C. Putignano, M. Ciavarella and J.R. Barber, Frictional energy dissipation in contact of nominally flat rough surfaces under harmonically varying loads, *J Mech Phys Solids* **59** (12), 2011, 2442–2454.

[24] M. Popov, V.L. Popov and R. Pohrt, Relaxation damping in oscillating contacts, *Sci Rep* **5**, 2015.

[25] A. Papangelo and M. Ciavarella, Effect of normal load variation on the frictional behavior of a simple Coulomb frictional oscillator, *J Sound Vib* **348**, 2015, 282–293.

[26] A. Papangelo and M. Ciavarella, On the limits of quasi-static analysis for a simple Coulomb frictional oscillator in response to harmonic loads, *J Sound Vib* **339**, 2015, 280–289.

[27] A.V. Dimaki, A.I. Dmitriev, N. Menga, A. Papangelo, M. Ciavarella and V.L. Popov, Fast high-resolution simulation of the gross slip wear of axially symmetric contacts, *Tribol Trans* **59** (1), 2016, 189–194.

[28] A. Papangelo, M. Ciavarella and N. Hoffmann, Subcritical bifurcation in a self-excited single-degree-of-freedom system with velocity weakening–strengthening friction law: analytical results and comparison with experiments, *Nonlinear Dyn* **90** (3), 2017, 2037–2046.

[29] Papangelo A, Ciavarella M, Barber JR. Fracture mechanics implications for apparent static friction coefficient in contact problems involving slip-weakening laws. In: Proc. R. Soc. A. vol. 471, No. 2180; 2015. p. 20150271. The Royal Society.

[30] A. Papangelo and M. Ciavarella, Cattaneo–Mindlin plane problem with Griffith friction, *Wear* **342**, 2015, 398–407.

[31] G. Grimaldi, A. Papangelo and M. Ciavarella, A Cattaneo-Mindlin problem for a rigid punch with tangential load applied above the interface line, *Proc Inst Mech Eng Part C: J Mech Eng Sci* **230** (9), 2016, 1410–1416.

Supplementary material

Multimedia Component 1

Supplementary data 1

Highlights

- Fretting fatigue has been studied mainly with constant normal load.
- Abbasi and Majzoobi ~~[1]~~ (2017) have in phase or out-of-phase varying normal load at the same frequency.
- Contact mechanics and numerical simulations seem at odd with the findings.
- If experiments are confirmed, varying normal load effect calls for some new models in fretting.

Queries and Answers

Query: The author names have been tagged as given names and surnames (surnames are highlighted in teal color). Please confirm if they have been identified correctly.

Answer: ok