Finite Element Investigation of Thermal Distribution in Fretting Fatigue

Ali Mousavi[1]

[1]*Mechanical Engineering department, Kashan University, Kashan, Isfahan, Iran.*

---***---

Abstract: A finite element model is developed for investigation of temperature development of fretting between a cylinder and flat surface. The model is based on the partial sliding between the surfaces and the friction in the sliding region is considered the source of heat generation as a form of surface heat flux acting on the boundary between the contacting parts. The results show that temperature rise around the contact can be used as a tool to predict the friction force.

Nomenclature

1. Introduction

The damage of mechanical parts under fatigue loading is a common cause of engineering structural damage. The oscillatory nature of motion and loading makes it a time-dependent damage. During the service life of parts under oscillatory loads, cracks may initiate and propagate due to the existing flaws in material due to manufacturing and other sites of stress concentration. The added stress concentration gives rise to the plastic deformation and the associated energy, ending in failure upon the continuation of loading. One form of failure may result due to surface contact of two components under oscillatory loading.

When two contracting surfaces are subjected to minute oscillation, the component is prone to have a damage in the form of fretting. There exist numerous instances where failure occurs due to fretting damage including bio-medical parts to rivet structures. As a complex phenomenon, fretting is the reason for two types of damage which are wear and crack initiation. Wear is commonly characterized as the gross sliding while crack initiation is related to partial slip of two surfaces. There has been models to study effect of fretting on life of components. In most of models the stress-strain relations are used to predict the amount of the heat generation which are ultimately related to the development of damage. This is crucial for many applications to monitor the components under fretting and predict life of parts based on the measurable quantities. This is shown here that temperature rise can be used as a parameter to find the dissipated energy [1] which is related to fretting damage.

Thermal imaging techniques are widely used for damage accumulation of metals due to crack propagation [2-5]. Using thermography, wang et al measured the crack tip dissipated energy and developed a fatigue crack growth model [6]. Jirandehi et al [1], proposed a criterion for determining the critical load limit of cyclic inelastic buckling of metals. They used thermal imaging and obtained the critical temperature required for the occurrence of this formal failure. It was postulated that below a stress level this form of failure does not occur and the value was determined based on fracture fatigue entropy (FFE). Bayati et al [7] used IR camera to track the heat dissipation and temperature evolution of additively manufactured material under cyclic loading. Accordingly, they assessed the fatigue properties including fatigue limit via the so-called self-heating method. In a series of work Hajshirmohammadi et al studied the fatigue crack growth behavior via thermal imaging. The stress intensity factor and temperature rise in the crack growth site were correlated and a relationship between crack propagation rate and temperature rise was proposed [8, 9]. In addition, the accumulated entropy associated with fatigue crack growth was measured [4]. Fretting fatigue which is a type of damage accumulation process can also be seen as a process of dissipation and there would be a potential for its monitoring based on infrared monitoring.

Studying of fatigue damage accumulation during fretting has been a main concern for the last two decades [10-12] . Damage accumulation and energy approaches have been proved to put forward reliable results [13-18].for analyzing fatigue damage. Chen et al [19], investigated the local sites of crack nucleation under cyclic loading. They indicated that the locations of maximum locally stored energy best correlates with the crack nucleation sites. Crystal plasticity finite element simulations was performed to assess the behavior. Moreover, other factors such as dislocation density and dissipated energy were assessed. Jirandehi et al [15] developed a model for the statistical estimation of microplastic strain energy (SEPSE) under cyclic loading. The energy-based approach is also implemented in investigating initiation and propagation of crack in components susceptible to fretting fatigue. Fellows et al [13] proposed a microscopic approach to the prediction of crack initiation under fretting fatigue. They proposed technique determines the ratio of specimen life in the initiation and propagation regions of fretting fatigue. Principles of continuum damage mechanics were utilized by Hojatti et al [20] ,to develop a damage evolution law for the prediction of fatigue crack initiation to propagation life ratio under fretting fatigue. It is worth mentioning that eXtended finite element was used for the calculation of crack growth region. The prospective field of energy analysis of fretting fatigue is the incentive for development of new techniques which ease the quantitative characterization of fretting fatigue. The new improvements in infrared devices have made energy-based methods applicable to industrial needs.

Theory and formulation

It is generally accepted that onset of fretting involves crack nucleation to a critical length which can lead to crack growth where the material is under bulk fatigue loading. This means that to find the crack initiation point, it is needed to find the stress distribution around the contact region. The energy which is dissipated during the small sliding in the partial-sliding region is the results of surface friction and the finite movement of the sliding parts. Fig. 1 shows the schematic of an oscillating half-cylinder on a flat. The well-known elliptical distribution predicts the pressure in the contact region as follows.

$$P(x) = P_0 \left\{1 - \left(\frac{x}{a}\right)^2\right\}^{1/2} \quad (1)$$

$$P_0 = \left(\frac{PE}{2\pi(1-\nu^2)r}\right)^{1/2} \quad (2)$$

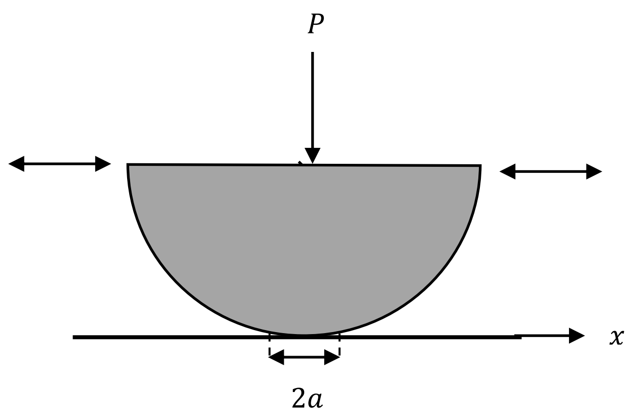
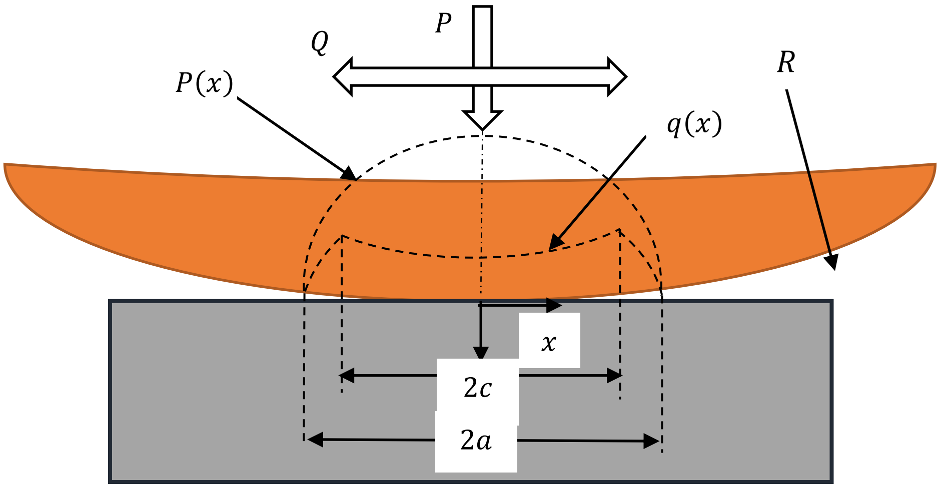


Figure 1. schematic of fretting contact

In these relations, a is the width of contact region and the peak pressure is shown by P_0. In Eq. 2 E is the elastic modulus and Poisson's ratio is given by ν. When a shear stress is applied on the cylinder, and the friction force is enough to prevent the surfaces from gross sliding, there will be distinct regions of contact as shown in Fig. 2. As it is seen in Fig. 2, the central part of the contact which has the length of $2c$, is stuck and there is no relative sliding between the surfaces in that region. In the area around the central part, the two surfaces slide and has relative movement on each other. The surface traction is given as q and can be calculated in different regions according to the given relation.



$$q = \mp\mu P_0(1 - x^2/a^2)^{0.5}, \quad b \le |x| \le a$$

$$\mp\mu P_0(1 - x^2/a^2)^{0.5} - 2\frac{b}{a}(1 - x^2/b^2)^{0.5} \quad , \quad c \le |x| \le b$$

$$\mp\mu P_0(1 - x^2/a^2)^{0.5} - 2\frac{b}{a}(1 - x^2/b^2)^{0.5} + \frac{c}{a}(1 - x^2/c^2)^{0.5}, \quad |x| \le c$$

Figure 2. Schematic of fretting contact zone and relations.

The region where partial slip happens is where the heat is generated which is $c \le |x| \le b$.

As the heat is generated, the surrounding faces experience a temperature rise which is directly related to the amount of energy dissipated during the movement of surfaces. In the following a finite element model is presented to calculate this temperature rise.

1.1. Numerical approach

Finite element method and numerical methods have proved to be a strong tools for the verification of results in many of the engineering fields [21-28]. Hence, an FEM is developed to study the fretting contact behavior. In order to implement the boundary conditions, the top of the half cylinder is subjected to normal force and oscillation in x direction. The load is implemented in two steps. In the first step, the normal load is applied on the top of the cylinder and in the second step the horizontal load is applied. To restrict the movement of the flat, the bottom line of the plane is set to zero displacement in vertical and horizontal direction. This restriction of movement is implemented in the initial step before the normal load.

The classic Coulomb friction is used as the model for the contact friction. The friction coefficient is defined before the first step.

The node-to-surface contact discretization is used as the solution approach of contact. In this approach forces acting on the slave nodes are crucial for the convergence of contact algorithm.

Based on Fig. 3, contact pressure is distributed unevenly on the element in the three points. The force is four times larger than the side nodes. If the node-to-surface algorithm is used, this uneven distribution becomes source of error. The reason is that the variation of nodal loads can be due to variation of pressure on the element which may happen.

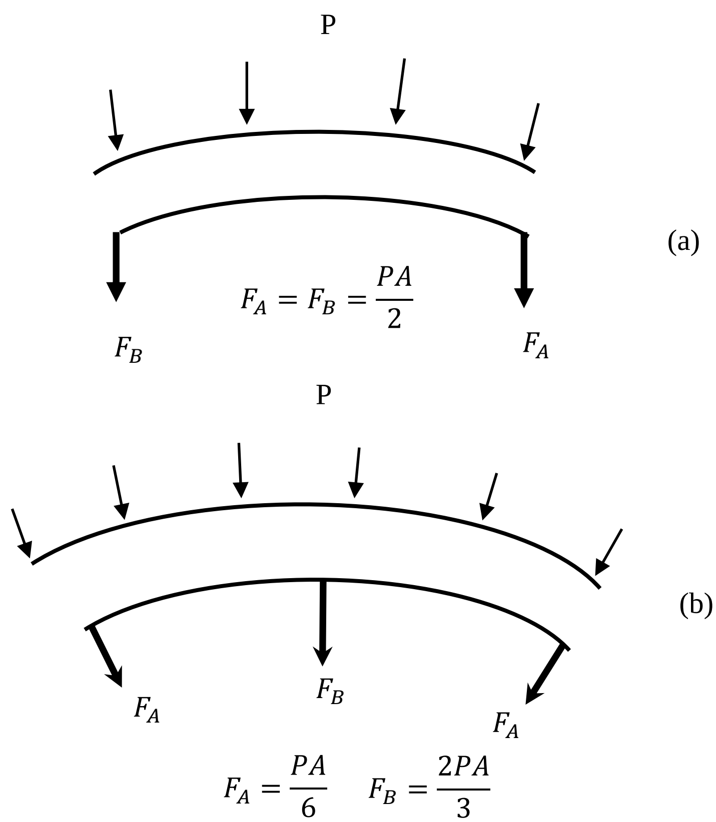


Figure 3. Nodal loads in a (a) first-order, and (b) second-order element.

Three-dimensional, second order elements have the same issue except for the nodal loads which have different signs when the pressure is constant. This issue makes the solution costlier if the algorithm used is node-to-surface. The solver, ABAQUS standard, adds mid-face nodes to surface as well as second order elements if node-to-surface method is chosen.

Fig. 4 depicts the two dimensional bodies in contact and the mesh. As it is shown in the figure, the mesh size is considered very small with the size of 2 μm in the contact region.

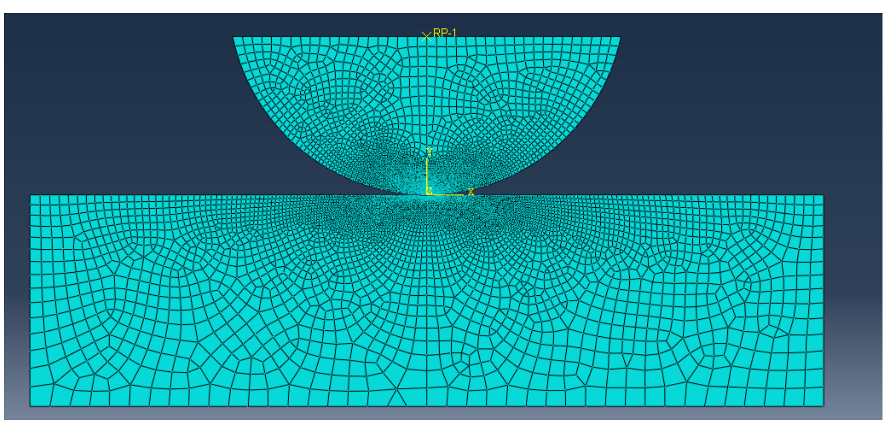


Fig. 4 Meshing of specimen and the pad for FE analysis

Both sides of the flat are restricted from movement to the left and right. The Multi-Point Constraint is applied on the top side of the cylinder to restrict its rotation. MPC are features letting the solution to connect nodes and degrees f freedom together in finite element analysis. MPC is used to enforce the boundary condition in conditions where normal boundary conditions do not give an appropriate solution.

The solution procedure diagram is shown in Fig. 5. As it is seen in Fig. 5, the solution is comprised of displacement-stress step (step 1) and thermal step (step 2). The first step is chosen to be static general in ABAQUS which uses the implicit scheme for

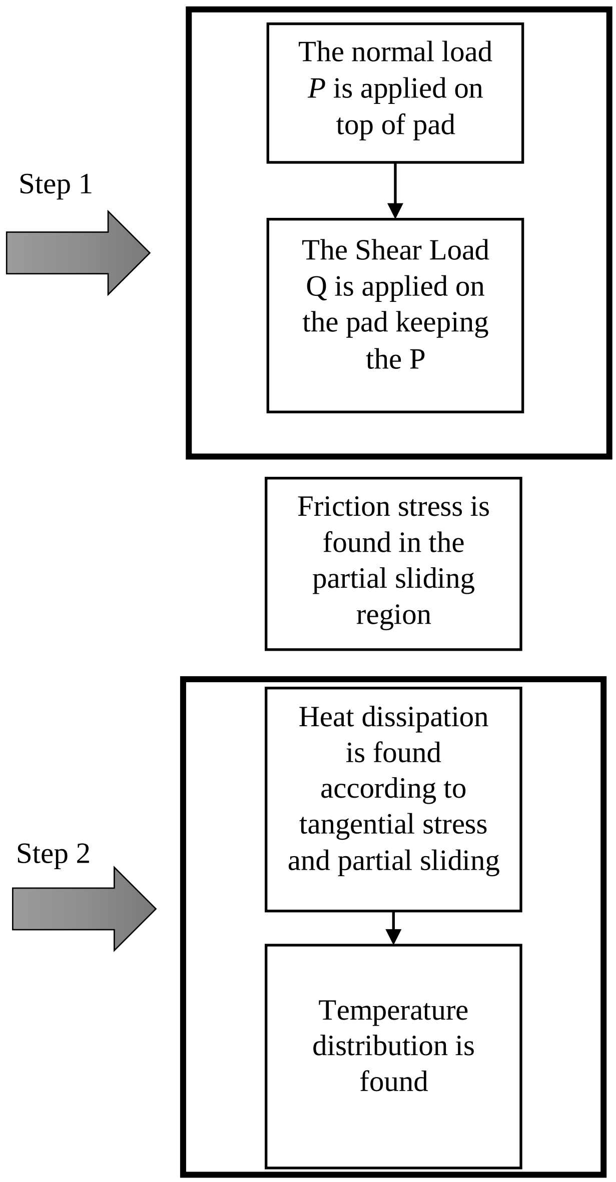


Fig. 5 Solution steps diagram

2. Results and discussion

The ABAQUS results are shown for the test specification mentioned in table 1.

Table 1. geometry and material properties of fretting contact problem shown in Figure 15.

E	F	R	ν	t	b
72.1 GPa	150 N	20 mm	0.33	10 mm	40 mm

The normal load is set to be 150 N and tangential load is 50 N. The present results are compared with [20]. As it is shown the stress distribution by the present simulation is in agreement with [20].

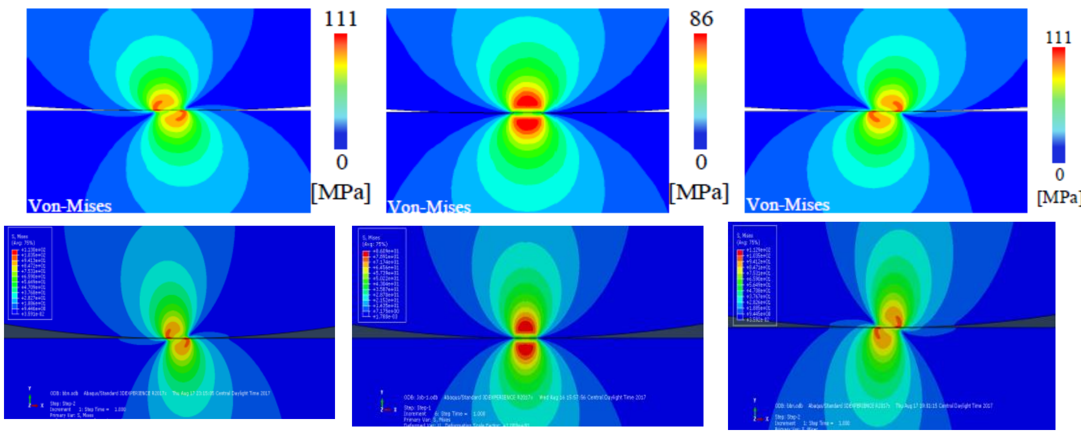


Fig. 6 Von misses stress in both specimen and pad in different stages of tangential load application.

If the slip region is taken as the place where rubbing two surfaces generates heat, the amount of energy dissipated in one cycle is found by

$$W = \int_{x_1}^{x_2} \sigma b \delta dx$$

in which σ is the shear stress b is the thickness of plate and x_1 and x_2 are the start and end location of the sliding region in contact area. In this relation δ is the relative sliding between the calendar and flat for each point in the partial slipping region.

The dissipated energy per area, which is considered as the heat flux between the two surfaces, is found by dividing dissipated energy W to the partial area of the contact region, bdx.

This amount of flux is due to one cycle of fretting. To calculate the total flux per second, it has to be multiplied by the frequency. The following relation gives the amount of heat flux as the result of contact sliding.

$$H = \int_{\substack{Partial\\ sliding\\ region}} f \sigma \delta$$

where f is the frequency of fretting. The stress can be achieved by the solution in both sticking and sliding region. In order to see the variation of stress we need to compare it in the two different zones. Following Figure shows the shear stress in the contact region

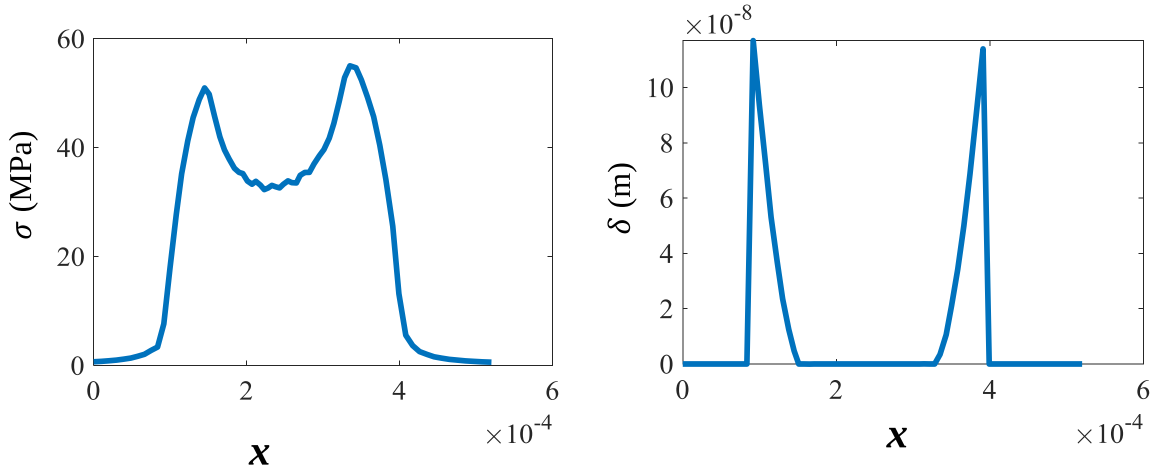


Fig. 7 Stress and slip in two zones of sticking and sliding between the specimen and the pad.

As it is seen in Fig. 7, the stress increases in x direction when we move from the center to the sides. The peak which is shown in both stress and partial sliding is the margin between the stick and partial slip zones. This point is the location of nucleation of cracks as the fretting process goes on. This point is the critical location for movement of dislocations and consequently formation of micro-cracks. These micro-cracks become larger as the fretting process continues. Because the specimen is subjected to a bulk load, after nucleation of crack the rest of damage is the result of plane fatigue in the material.

In the following figure, the energy flux on the boundary of the contact is shown for one cycle.

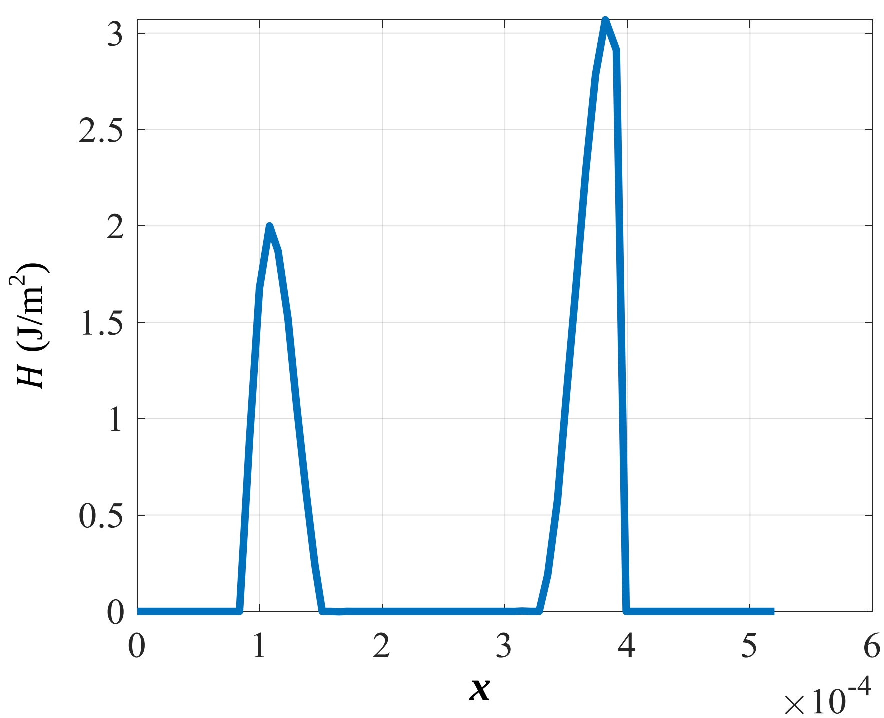


Fig. 8 Stress and slip in two zones of sticking and sliding between the specimen and the pad.

As it is seen in Fig. 8, the heat flux has two visible jumps in the total region of fretting. These two spikes represent the location of shift between the partial slip to the stick zone.

The thermal dissipation and temperature rise is found by a heat transfer simulation in ABAQUS. This requires one to link the solution from the displacement-load results to thermal FE simulation. In order to find the temperature rise, heat flux found in the previous step is given as the input to the heat transfer solution step. The element type is changed to heat transfer while the mesh is kept the same as displacement-load simulation. The temperature rise is shown in the following figure.

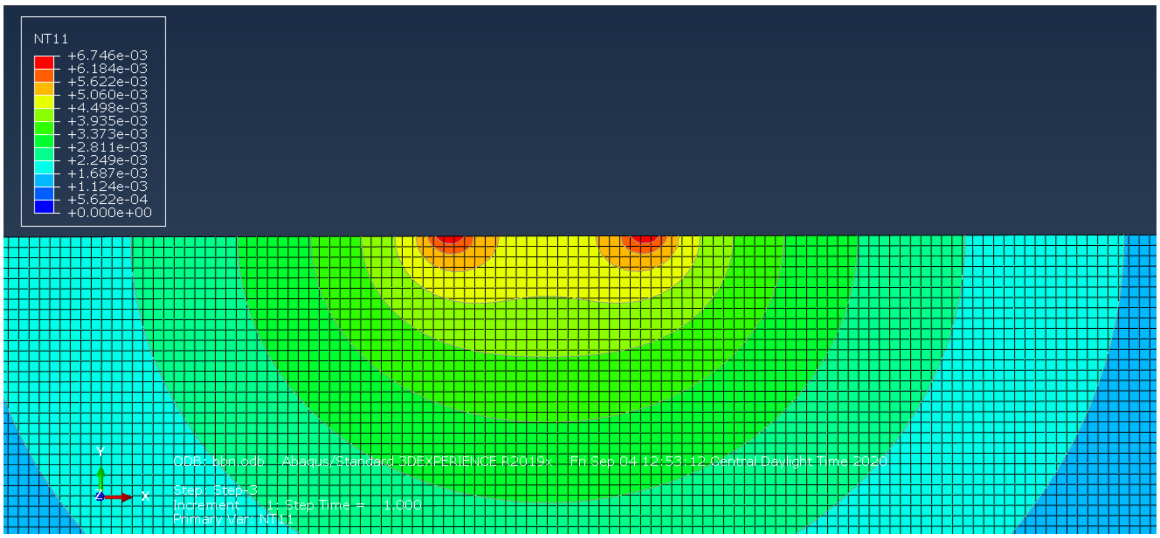


Fig. 9 Temperature distribution on the surface of specimen is fretting zone.

This is seen from the figure above that temperature distribution is symmetric around the axis of fretting normal load. The maximum temperature rise happens in the partial slip region where the contact faces has rubbing contact. As it is seen, the temperature rise is smaller in the central stick region where the two surfaces stick on each other.

3. Conclusions

A finite element analysis of fretting fatigue is presented for the purpose of finding temperature distribution in the contact of two sliding surfaces. The FEA is consisting of two steps. The first step calculates the stress distribution and partial sliding. The second step solves the thermal dissipation in the region of fatigue. It was shown that the dissipation can be generate heat and elevate the temperature of the two sliding surfaces. The thermal distribution is symmetric around the axis of fretting. Solution shows the potential of thermal imaging for investigation of fretting fatigue.

References

[1] A. P. Jirandehi, M. Mehdizadeh, and M. Khonsari, "Temperature-induced buckling of ductile metals during cyclic loading and the subsequent early fracture," International Journal of Mechanical Sciences, vol. 176, p. 105525, 2020.

[2] B. Hajshirmohammadi and M. Khonsari, "Thermographic evaluation of metal crack propagation during cyclic loading," Theoretical Applied Fracture Mechanics, vol. 105, p. 102385, 2020.

[3] B. Hajshirmohammadi and M. Khonsari, "A simple approach for predicting fatigue crack propagation rate based on thermography," Theoretical Applied Fracture Mechanics, vol. 107, p. 102534, 2020.

[4] B. Hajshirmohammadi and M. Khonsari, "On the entropy of fatigue crack propagation," International Journal of Fatigue, vol. 133, p. 105413, 2020.

[5] A. Haghshenas and M. Khonsari, "Non-destructive testing and fatigue life prediction at different environmental temperatures," Infrared Physics & Technology, vol. 96, pp. 291-297, 2019.

[6] X. Wang, H. Ran, C. Jiang, and Q. Fang, "An energy dissipation-based fatigue crack growth model," International Journal of Fatigue, vol. 114, pp. 167-176, 2018.

[7] P. Bayati et al., "Toward low and high cycle fatigue behavior of SLM-fabricated NiTi: considering the effect of build orientation and employing a self-heating approach," International Journal of Mechanical Sciences, p. 105878, 2020.

[8] B. Hajshirmohammadi and M. Khonsari, "Thermographic evaluation of metal crack propagation during cyclic loading," Theoretical and Applied Fracture Mechanics, vol. 105, p. 102385, 2020.

[9] B. Hajshirmohammadi and M. Khonsari, "A simple approach for predicting fatigue crack propagation rate based on thermography," Theoretical and Applied Fracture Mechanics, vol. 107, p. 102534, 2020.

[10] S. Fouvry, T. Liskiewicz, P. Kapsa, S. Hannel, and E. J. W. Sauger, "An energy description of wear mechanisms and its applications to oscillating sliding contacts," J Wear, vol. 255, no. 1-6, pp. 287-298, 2003.

[11] A. Aghdam and M. Khonsari, "On the correlation between wear and entropy in dry sliding contact," J Wear, vol. 270, no. 11-12, pp. 781-790, 2011.

[12] T. Liskiewicz and S. Fouvry, "Development of a friction energy capacity approach to predict the surface coating endurance under complex oscillating sliding conditions," J Tribology international, vol. 38, no. 1, pp. 69-79, 2005.

[13] L. Fellows, D. Nowell, and D. Hills, "On the initiation of fretting fatigue cracks," J Wear, vol. 205, no. 1-2, pp. 120-129, 1997.

[14] A. P. Jirandehi and T. Chakherlou, "A fatigue crack initiation and growth life estimation method in single-bolted connections," The Journal of Strain Analysis for Engineering Design, vol. 54, no. 2, pp. 79-94, 2019.

[15] A. P. Jirandehi and M. Khonsari, "On the determination of cyclic plastic strain energy with the provision for microplasticity," International Journal of Fatigue, vol. 142, p. 105966, 2020.

[16] K. Lijesh, M. Mehdizadeh, and M. M. Khonsari, "Online monitoring of metal fatigue life," Structural Health Monitoring, p. 1475921719871668, 2019.

[17] J. Jang, M. Mehdizadeh, and M. Khonsari, "Nondestructive estimation of remaining fatigue life without the loading history," International Journal of Damage Mechanics, vol. 29, no. 3, pp. 482-502, 2020.

[18] M. Mehdizadeh, A. Haghshenas, and M. Khonsari, "In-situ Technique for Fatigue Life Prediction of Metals Based on Temperature Evolution," International Journal of Mechanical Sciences, p. 106113, 2020.

[19] B. Chen, J. Jiang, and F. P. Dunne, "Is stored energy density the primary meso-scale mechanistic driver for fatigue crack nucleation?," International Journal of Plasticity, vol. 101, pp. 213-229, 2018.

[20] R. Hojjati-Talemi, M. A. Wahab, E. Giner, and M. Sabsabi, "Numerical estimation of fretting fatigue lifetime using damage and fracture mechanics," Tribology Letters, vol. 52, no. 1, pp. 11-25, 2013.

[21] H. Rahmaninejad, T. Pace, S. Bhatt, B. Sun, and P. Kekenes-Huskey, "Co-localization and confinement of ecto-nucleotidases modulate extracellular adenosine nucleotide distributions," PLoS computational biology, vol. 16, no. 6, p. e1007903, 2020.

[22] S. Onsorynezhad and F. Wang, "Discontinuous dynamics of a frequency up-Conversion piezoelectric harvester," in International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2019, vol. 59285: American Society of Mechanical Engineers, p. V008T10A037.

[23] S. Onsorynezhad, A. Abedini, and F. Wang, "Parametric optimization of a frequency-up-conversion piezoelectric harvester via discontinuous analysis," Journal of Vibration and Control, p. 1077546319894797, 2020.

[24] K. W. Buffinton, B. B. Wheatley, S. Habibian, J. Shin, B. H. Cenci, and A. E. Christy, "Investigating the Mechanics of Human-Centered Soft Robotic Actuators with Finite Element Analysis," in 2020 3rd IEEE International Conference on Soft Robotics (RoboSoft), 2020: IEEE, pp. 489-496.

[25] S. Habibian, "Analysis and Control of Fiber-Reinforced Elastomeric Enclosures (FREEs)," arXiv preprint arXiv:1912.07380, 2019.

[26] H. Mousavi and C. Sandu, "Sensitivity analysis of tire-ice friction coefficient as affected by tire rubber compound properties," Journal of Terramechanics, vol. 91, pp. 319-328, 2020.

[27] H. Mousavi and C. Sandu, "Tire-ice model development for the simulation of rubber compounds effect on tire performance," Journal of Terramechanics, vol. 91, pp. 97-115, 2020.

[28] C. Liang, L. Ji, H. Mousavi, and C. Sandu, "Evaluation of tire traction performance on dry surface based on tire-road contact stress," in SIAR International Congress of Automotive and Transport Engineering: Science and Management of Automotive and Transportation Engineering, 2019: Springer, pp. 138-152.