Contact slip prediction in HAp coated artificial hip implant using finite element analysis

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Abstract
The rapid age growth in most of the developed countries leads to application of artificial joints such as knee joints and hip joints. The properties of titanium alloy such as light weight, high strength and good biocompatibility make it a suitable material for wide usage as artificial joints. However, titanium alloy cannot directly adhered with human bone; thus, bonds or coating are required. Plasma-sprayed hydroxyapatite (HAp) is widely used as a coating to bond artificial Ti-6Al-4V implants with human bone. The contact slip mainly occurs at the HAp-Ti-6Al-4V interface which also known as possible delamination interface in hip joint artificial implant. The coating fretting fatigue delamination condition can lead to contact slip at HAp coating-Ti-6Al-4V interface which will accelerate HAp coating fretting wear behavior. This paper presents the influence of normal loading, fatigue loading and delamination length on contact slip distributions at HAp coating-Ti-6Al-4V interface through finite element based methodology. A simple FE contact configuration model consist of contact pad, HAp coating and Ti-6Al-4V substrate is examined under static simulation. The predicted results revealed that lower normal load with higher maximum fatigue loading condition could promote more contact slip distribution. The contact slip is also increased with increasing delamination length. The induced contact slip can accelerates fretting wear behavior of HAp coating.

Keywords: Hydroxyapatite, Ti-6Al-4V, Contact slip, Interface, Hip joint

1. Introduction

Recently, researchers have shown an increased interest in surface coatings application to improve wear resistance which can prolong life of components (Mohd Tobi et. al., 2015; Nagentrau et. al., 2017; Nagentrau et. al., 2017). The rapid age growing in most of the developed countries leads to application of artificial joints such as knee joints and hip joints (Otsuka et. al., 2016). The artificial joints commonly made of titanium alloy. The interesting characteristics of titanium alloy such as light weight, high strength and good biocompatibility make it a very suitable material for extensive usage as artificial joints (Siswanto et. al., 2016; Nagentrau et. al., 2016; Nagentrau et. al., 2016).

However, titanium alloy cannot directly adhered with human bone. It is noteworthy to mention that such a condition leads to the necessities of bonds or coating (Niinomi, 2007). There is great requirement for high performance material in coating in order to provide protection to the components that operating under wear environment (Sun et. al., 2001). Hydroxyapatite HAp:Ca₁₀(PO₄)₆(OH)₂) promotes bond between titanium alloy and bone since it contains main composition of human bone (Sun et. al., 2001). In addition, plasma-sprayed HAp coating regularly used on the metallic implant surfaces in biomedical applications (Otsuka et. al., 2016).

The long-term usage of HAp coating can challenge its efficiency in promoting bonds between artificial joints and human bone (Chung et. al., 2009; Tonino et. al., 1999). The HAp coating tends to fail by the reasons of brittle fracture,
fatigue cracks, fretting delamination and fretting wear (Geesink and Hoefnagels, 1995; Hernandez-Rodriguez et. al., 2010). The contact slip mainly occurs at the HAp coating-Ti-6Al-4V interface which also known as possible delamination interface in hip joint artificial implant as shown in Figure 1. The coating fretting fatigue delamination condition can lead to contact slip at HAp coating-Ti-6Al-4V interface which will accelerate HAp coating wear behavior as shown in Figure 2.

Wear debris (particles) due to fretting able to activate inflammation at surrounding organs which can lead to loosening of implants and associated subsequent failure (Otsuka et. al., 2016). A considerable amount of literature has been published on premature failure of these implants due to wear attributed to implant loosening (Langton et al., 2011, Mattei et al., 2011). The Sweetish Hip Arthroplasty Registry reported that 75% hip implant loosening is caused by the loss of fixation of the implants. Such a loss of fixation is due to a result of inadequate initial fixation, mechanical loss of fixation over time or biologic loss of fixation is caused by fretting wear. It possibly occur at modular stem-bone (cemented or uncemented) or the head-taper interface (Abu-Amer et al., 2007).

It is noteworthy to mention that failure of HAp coating in hip joint artificial implant can increase a risk of revisions. However, as far as author’s knowledge, there are still lack of studies on contact slip behaviors of HAp coating by fretting fatigue that can appropriately mimic actual loading conditions of artificial hip implants. Besides that, the understanding on contact slip behaviors at HAp-Ti-6Al-4V interface should be polished as lack of fundamental understanding in term contact mechanics analysis in artificial hip implant. Minimizing contact slip which leads to delamination fretting wear failure in artificial hip implant is often necessary because such a flaw is life threatening and also costly.

This study aims to focus the contact slip behavior at HAp coating-Ti-6Al-4V interface using static finite element analysis. The influence of normal loading, fatigue loading and delamination length on predicted contact slip distributions is studied in detail. This study is significant to prolong the HAp coating service life in hip joint artificial implants.

Fig. 1 Possible delamination interface in hip joint artificial implant

Fig. 2 Delamination fretting wear failure mechanism at at HAp-Ti-6Al-4V interface
2. Finite element simulation

2.1 Material

The material examined in this particular study is hydroxyapatite (HAp) which is widely used as a coating to bond artificial metallic implants with human bone. In addition, titanium alloy (Ti-6Al-4V) which commonly used as artificial metallic implants is assigned as substrate. Meanwhile, PP resin is assigned as contact pad which represents human bone. The Young’s modulus and Poisson’s ratio of coating, substrate and contact pad are presented in Table 1 referring to earlier studies (Otsuka et. al., 2013; Ren et. al., 2009). The elastic modulus of PP resin contact pad is taken as 1 GPa based on experimental study conducted by Otsuka et. al., (2013). A porous polypropylene (PP) resin (50pcf, Avis) is used to represent cancellous bone as contact pads.

Table 1 Material properties data.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V substrate</td>
<td>110</td>
<td>0.33</td>
</tr>
<tr>
<td>HAp coating</td>
<td>70</td>
<td>0.24</td>
</tr>
<tr>
<td>PP resin contact pad</td>
<td>1</td>
<td>0.35</td>
</tr>
</tbody>
</table>

2.2 FE modelling approach

A commercial FE software ABAQUS/Standard is employed throughout the static numerical analysis to predict the contact slip distribution at HAp coating-Ti-6Al-4V interface. Figure 3 illustrates the schematic view of the contact configuration model. The FE geometrical model is based on the experimental configuration of fretting fatigue test arrangement that assigned in earlier studies (Otsuka et. al., 2006). The model comprised of a contact pad, coating and substrate.

Figure 4 shows the corresponding two dimensional (2D) 1/4 symmetric FE model used throughout the simulation. The FE configuration is modelled as 2D by the reason of plane strain case of the problem. The FE model assumed as an elastic half space. Mainly, two parts are modelled for this simulation where contact pad and coating modelled as one single part, meanwhile another part is substrate. The HAp coating thickness is 0.15 mm. The complete assembly of FE model is partitioned as shown in Figure 4 with the purpose of assigning the material and mesh optimization. Figure 5 shows the mesh module of the FE model.

The FE model is discretized into linear quadrilateral plane strain elements. Finer mesh is applied at the contact region, meanwhile coarse mesh is used at further region. Mesh refinement at contact region is achieved by edge seeding technique. An appropriate mesh size of 50 µm is assigned at the contact region and claimed as quality mesh since additional mesh refinement gives a negligible effect on predicted contact slip. The mesh refinement at the contact region...
is mainly to obtain better contact slip prediction with reasonable analysis computational time.

The bottom surface of the substrate is constrained from all displacements and rotations. Meanwhile, the boundary condition of the whole model side surface enables vertical displacement only. The loading condition used in the FE modelling are normal loading of (20 and 30 MPa), fatigue loading of (250 and 300 MPa), stress ratio (R=0.1) and delamination length (0.2, 0.5 and 1.0 mm). The tie constraint technique is practiced to control the variation in delamination length. Surface to surface contact technique is assigned where two types of the contact pair surfaces introduced, i.e. master and slave; the coating (HAp) acts as the master surface while the substrate (Ti-6Al-4V) as the slave surface. The Lagrange multiplier contact algorithm is used in the contact surface interaction properties with the coefficient friction, of 0.7 obtained from the earlier study performed by Yugeswaran et.al. (2012). The Lagrange multiplier contact algorithm is chosen to ensure the exact sticking condition where shear stress is lower than the critical shear stress based on Coulomb friction. Then the static simulation is performed by using three steps.
Contact configuration model | Normal stress (MPa) | Maximum fatigue stress (MPa) | Delamination length (mm)
--- | --- | --- | ---
1 | 20 | 250 | 1.0
2 | 20 | 300 | 1.0
3 | 30 | 250 | 1.0
4 | 30 | 300 | 1.0
5 | 20 | 300 | 0.2
6 | 20 | 300 | 0.5
7 | 20 | 300 | 1.0

Static general step is performed with the time period of one (1) second and maximum of hundred (100) increments. The boundary condition is applied in initial step where the bottom and side surface of the model are constrained as shown in Figure 4. Normal load is applied in Step-1, maximum fatigue loading in Step-2 and followed by minimum fatigue loading in Step-3. The results of contact slip (CSLIP) is extracted from the pathline created at the coating-substrate interface. Table 2 presents seven different contact configuration models to study the contact slip response throughout the simulation. In fact, the delamination length is kept constant when investigating the influence of normal and fatigue loading. Meanwhile, similar normal and fatigue loading are maintained to study the effect of delamination length.

### 3. Results and Discussion

#### 3.1 Influence of normal load and fatigue load on contact slip distribution

Figure 6 presents the contact slip distribution at HAp coating-Ti-6Al-4V interface under different fatigue and normal loadings. The contact slip distribution is analyzed for three (3) conditions, i.e. normal load only (Step-1), maximum fatigue loading (Step-2) and minimum fatigue loading (Step-3) as shown in Figure 6a, 6b and 6c respectively.

From the data in Figure 6a, it is apparent that there is very minimal contact slip (nearly zero) is registered during the normal load only condition. The highest contact slip values is recorded during maximum fatigue loading condition as illustrated in Figure 6b. Meanwhile, contact slip distribution during minimum fatigue loading condition indicates lower magnitude compared to maximum fatigue loading condition as shown in Figure 6c.

Figure 6 is quite revealing that the higher magnitude of the contact slip is noted at the contact edge and decreasing at the further region for both maximum and minimum fatigue loading conditions respectively. The result indicates that lower normal load (20 MPa) with higher fatigue loading (300 MPa) results in significant contact slip. In the meantime, the lowest contact slip is recorded for the higher normal load (30 MPa) with lower fatigue loading (250 MPa). It is noteworthy to mention that the delamination length (1.0 mm) is kept constant for all cases in order to focus the effect of normal and fatigue loading on contact slip.

Figure 7 indicates the contact slip distribution for several (two) cycles for the elements experiencing maximum and minimum contact slip respectively. The contact mechanical behavior may change after the first cycle because frictional contact problems are path-dependent problems. Therefore, more than one cycle is simulated using the normal load (20 MPa) and maximum fatigue load (300 MPa) which leads to maximum contact slip. This evidences that the contact slip reach stable state.
Fig. 6 Contact slip distribution under different normal and fatigue loading, (a) normal load only, (b) maximum fatigue loading and (c) minimum fatigue loading.

Fig. 7 Contact slip distribution for several cycles for maximum and minimum contact slip elements.
3.2 Influence of delamination length on contact slip distribution

Figure 8 exhibits the contact slip distribution at HAp coating-Ti-6Al-4V interface under different delamination lengths. Three (3) main conditions such as normal load only (Step-1), maximum fatigue loading (Step-2) and minimum fatigue loading (Step-3) are focused as illustrated in Figure 8a, 8b and 8c respectively.

Similar to previous case, very minimal contact slip (nearly zero) is recorded during the normal load only condition as shown in Figure 8a. The maximum fatigue loading condition shows highest contact slip values as illustrated in Figure 8b. Meanwhile, contact slip distribution during minimum fatigue loading condition indicates lower magnitude compared to maximum fatigue loading condition as presented in Figure 7c. The significant contact slip is noted at the contact edge and reducing at the further region for both maximum and minimum fatigue loading conditions respectively. There is a clear trend of increasing in contact slip when delamination length is increased. The lower contact slip is noted for minimum delamination length (0.2 mm) and higher contact slip is registered for maximum delamination length (1.0 mm). Similar amount of normal and fatigue loading (20MPa, 300 MPa) are maintained throughout the investigation of delamination length effect on contact slip distribution.

One of the significant finding emerge from this study is fluctuation of contact slip noted in the cases of minimum fatigue loading as shown in Figure 6 and 8. This is mainly because the additional constraint that need to overcome the friction of the mating surfaces as normal loading effect is significant during minimum fatigue loading compared to maximum fatigue loading.

Fig. 8 Contact slip distribution under different delamination length, (a) normal load only, (b) maximum fatigue loading and (c) minimum fatigue loading
The discussion of the results begins with the peak contact slip noted at the contact edge during maximum and minimum fatigue loading conditions for all cases. Peak contact slip at the contact edge is dictated by the stress singularity effect due to sharp edge contacts. Stress singularities occur due to appliance of a point load, sharp re-entrant corners, corners of bodies in contact and point restraints. The stress concentration at the contact edges causing stronger force is distributed over that particular region together with increased stretching (maximum fatigue loading effect) and resulting in higher magnitude of contact slip.

The results of the present study where significant contact slip is noted for lower normal load (20 MPa) with higher fatigue loading (300 MPa) suggests that normal stresses are insufficient to prevent relative motion due to tangential traction caused by significant maximum fatigue stress condition at the HAp coating-Ti-6Al-4V interface. Among the plausible explanation of noted maximum contact slip for higher delamination length (1.0 mm) is due to increment in delamination length reduces the interfacial strength because induced tangential tractions caused by maximum fatigue loading at the HAp coating-Ti-6Al-4V interface. The higher delamination condition can lead to significant contact slip at HAp coating-Ti-6Al-4V interface which will promote HAp coating wear (Otsuka et. al., 2016).

4. Conclusion

The influence of normal loading, fatigue loading and delamination length on contact slip distributions at HAp coating-Ti-6Al-4V interface is studied in detail. The predicted outcome of the numerical analysis allow following conclusions to be made:

- Peak values of contact slip at the contact edge is as the result of stress concentration at sharp edges.
- Lower normal load (20 MPa) with higher fatigue loading (300 MPa) promote more contact slip due to significant relative motion of the HAp coated Ti-6Al-4V due to tangential traction caused by significant maximum fatigue stress.
- Increased delamination length result in more contact slip since reduction in interfacial strength due to tangential traction by fatigue stress.

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