Attracting Cracks for Arrestment in Bone-like Composites

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Background :-

- Imitation of nature to tackle failure due to cracks in composite.
- Crack causes failures in engineering materials before their yield/ultimate strength is reached.
- Cracks are present in bones as in engineering materials.
- Crack resistant osteonal bones attracts the crack to particular area in bones and then repair it.
Objective:-

• To investigate the effect of the osteon properties and size variation on crack stability and crack propagation.
• Whether cracks can be attracted to osteons for arrestment or not.
• Developing methodology to optimally designing the crack resistant engineering material.
Principal of crack arrestment in osteonal bones:-

Crack arrestment in osteons bones are based on the principal that cracks are always attracted toward the area where elastic modulus is less relative to rest of the material.

Terminology:-

• Inclusions- Part of the osteonal bones having tissue structure different from rest of the bone and have young modulus relatively less then rest of the bone.
• Interstitial- Remaining area in the osteonal bones excluding inclusions.
• Osteons- These are the inclusion in osteonal bones made up of cement line, Intra-Osteon Lamellae and Haversian Canal.
Fig. 1 Features of typical osteonal bone

Fig. 2 Microcracks in osteonal bone.
Effect of crack location, inclusion size and properties on crack propagation:

- Model 1: Two inclusion model
  This model is used to determine the effect of inclusion size and properties, crack location on the crack stability.

Fig. Two inclusion model.
Crack propagation criterion:-

• Two approaches are there which predict the similar results.
• Crack propagates when stress intensity factor $K$ reaches $K_c$ (Fracture Toughness) or potential energy release rate $G$ reaches $G_c$ (Critical energy release rate).
• $\frac{K^2}{E_o} = G$ This equation represent the relation between two criteria.
• Most of the calculations in paper are done by maximum circumferential stress analysis.
Observations From Two-inclusion Model

- \( \frac{E_1}{E_0}, \frac{E_2}{E_0} \) are the normalized values of young modulus of two inclusions.
- Calculations from finite element model says that if \( r_1, r_2, d_1, d_2 \) remain constant and we decrease the \( \frac{E_1}{E_0}, \frac{E_2}{E_0} \) crack instability increases, which is observed by increase in stress intensity factor of corresponding crack tip.
- If we make \( \frac{E_1}{E_0}, \frac{E_2}{E_0} \) and \( d_1, d_2 \) constant and changes \( r_1, r_2 \) stress intensity factor increases with corresponding increase in \( r_1 \& r_2 \).
- If we decreases \( d_1, d_2 \) keeping other quantities constant corresponding \( K \) values of crack tip increases.
One important fact is also observed that when quantities for particular crack tip are changed keeping the all quantities of inclusion near to other crack tip constant the similar effect on K values are observed for both crack tips but with less intensity for the crack tip for which corresponding values are constant.

Four Inclusion Model
This model describes the condition when crack has to turn at angle to be attracted by inclusion.

When crack is in between the two inclusion and they are symmetric geometrically and property wise crack will not be attracted to any of the inclusion. So we have to break the symmetry to make sure crack is attracted by any of the inclusion.

To find the angle of crack propagation $\theta$, $\frac{G_\theta}{G_o}$ is calculated as a function of $\theta$, crack will propagate in the direction in which value of this ratio is maximum.

It is observed that $\theta$ depends upon the properties of the corresponding inclusion (inclusion 1) as well as the properties of the inclusion on the opposite side (inclusion 4).
It is observed that crack propagation angle is increased toward inclusion one when its elastic modulus is decreased or elastic modulus of inclusion four is increased.

**Optimization of Elastic Modulus of Inclusions**

- A genetic algorithm was used to optimize the elastic modulus of four inclusions keeping other quantities constant for five initial angles of crack to horizontal \( \theta = 0°, 30°, 60°, 120°, 150° \)
All inclusion have effective elastic moduli smaller than that of interstitial material.

The effective elastic values are not symmetric about any of the crack tip. The asymmetry of neighboring inclusions in both geometry and material properties help in attracting cracks.

<table>
<thead>
<tr>
<th>$E_1/E_0$</th>
<th>$E_2/E_0$</th>
<th>$E_3/E_0$</th>
<th>$E_4/E_0$</th>
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<tbody>
<tr>
<td>0.01</td>
<td>0.20</td>
<td>0.01</td>
<td>0.28</td>
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Conclusions

- Inclusions with $\frac{E}{E_o} < 1$ decrease the stability of a crack initiated in interstitial material.
- Crack propagation direction can be changed by varying inclusions’ sizes and elastic properties.
- Inclusion symmetry about crack decreases the tendency to attract crack.
- Crack resistant engineering structures can be designed either by optimizing selected inclusion sizes and elastic properties or by randomly generating a sufficient number of inclusions with different sizes and elastic properties.
Thank you