Effect of Scarf Angle and Bond Thickness on Strength of Epoxy Adhesively Joints of Dissimilar Adherends

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In this study, strength of epoxy adhesively bonded scarf joints of dissimilar metals, namely SUS304 stainless steel and YH75 aluminium alloy was examined on several scarf angles and various bond thicknesses under pure mode I loading. Scarf angle, $\theta = 45^\circ, 60^\circ$ and $75^\circ$ were employed. The bond thickness, $t$ between dissimilar metals was controlled to be ranged between 0.1 mm to 1.2 mm. Finite element analysis was also executed to investigate the stress distributions in the scarf joints by ANSYS 11 code. Stress multiaxiality of scarf joints slightly increases as the scarf angle increases. From analytical solutions, stress singularity exists most pronouncedly at steel/adhesive interface corner of joint having $45^\circ$ to $75^\circ$ scarf angle and this is in agreement with FE analyses and is confirmed by fracture observations wherein the fracture has always been initiated at this point. The apparent Young’s modulus of adhesive layer in scarf joints is found to be 1.5-5 times higher than those of bulk epoxy adhesive, which obtained from tensile tests.

Key Words: epoxy adhesive, scarf joint, tensile test, fracture mechanics, finite element analysis

1. Introduction
Mechanical behavior and strength of adhesive joints depend extremely on stress states and fracture resistance properties of the adhesive layer. In the literature, many works have been directed on elucidating the mechanical and fracture behavior of sandwiched adhesive joints. These included investigations upon effect of joint geometry and crack path propagation, assessment of fracture initiation criteria and prediction of joint strength. Most of these investigations considered only joints with similar adherend, however, study on sandwiched dissimilar materials joints is hardly available thus motivated this work. It is predicted that the latter behaves slightly differ in comparison to the former due to the more complex elastic mismatches incorporated.

In this study, fracture tests of epoxy adhesively-bonded scarf joints of dissimilar metals were conducted under a remote tension load on several scarf angles and various adhesive bond thicknesses. Effect of joint geometry (i.e. bond thickness and scarf angle) upon strength of scarf joints will be qualitatively discussed.

2. Experimental procedures
The epoxy adhesive resin used in this study was Hi-Super 30 produced by Cemedine Co., Japan. This is a commercial brittle epoxy adhesive which can be cured at room temperature approximately in 30 minutes. The adhesive was mixed thoroughly prior to bonding by mixing the epoxy resin and hardener with the conditioning mixer for 1 min: 3 min schedule of diffusion and de-foaming, respectively. The mechanical properties of the bulk epoxy adhesive have been reported in our previous study [1], and the pertinent results are tabulated in Table 1.

To obtain the strength and fracture behavior of adhesive joints, scarf joint specimens were prepared. The dimensions of scarf joint are shown in Fig. 1. The adherents were consisted of SUS304 stainless steel and YH75 aluminium alloy. Prior to bonding, bonding surfaces were uniformly polished with # 2000 waterproof abrasive paper and afterward degreased with acetone. Adhesive bond thickness, $t$ inside a scarf joint was controlled by using a developed fixture and was varied between 0.1 mm to 1.2 mm. All specimens were cured at R.T. over 24 hours. After specimens were totally cured, four strain gages were mounted on bonding line; two in the longitudinal direction (i.e side of plate) and another two perpendicular to bonding line. Tensile fracture tests of scarf joints were carried out by a universal tensile test machine (INSTRON).

All specimens were tested at R.T. with the crosshead speed held constant at 0.5 mm/min.

3. Stresses in adhesive layer of scarf joints
Figure 2 shows the coordinate system which is typically used to evaluate stresses and strains in the central region of adhesive layer in scarf joints. For scarf joints loaded axially with average stress, $\sigma_0$, normal and shear stresses are given as:

$$\sigma_n = \sigma_0 \sin^2 \theta$$

(1)

and

$$\tau_{SN} = \sigma_0 \sin \theta \cos \theta$$

(2)

respectively. Another stresses acting in $s$ and $z$ directions are:

$$\sigma_{sNS} = \sigma_L = \sigma_y \sqrt{1 - \nu^2} / (1 - 2\nu)$$

(3)

From these stresses, maximum and minimum principal stresses can be derived as:

$$\sigma_{1,3} = \sigma_n + \sigma_{SN} \pm \sqrt{(\sigma_n - \sigma_{SN})^2 + 4\tau_{SN}^2} / 2$$

(4)

In addition, Mises equivalent stress is given as:

$$\sigma_{eq} = \sqrt{\left(\sigma_1 + \sigma_2 + \sigma_3\right)^2 - 3\sigma_1\sigma_2}$$

(5)

and hydrostatic stress is given as:

$$\sigma_{hys} = \left(\sigma_1 + \sigma_2 + \sigma_3\right)/3$$

(6)

4. Asymptotic solution of stress singularity
It is well known that when adhesive joint is subjected to a remote uniaxial load, within linear elasticity context, the asymptotic stress field develops at the vicinity of interface corners and exhibits singularity behavior of form $\sigma \approx H^{-\lambda}$ where $\sigma$ is the stress, $H$ is distance from the interface corner, $H$ is intensity of stress singularity and $\lambda$ is the order of stress singularity. There is already some experimental evidence, which emphasized that $H$ and $\lambda$ parameters can be effectively used to successfully predict the onset of failure and eventually evaluate the relationship between bond thickness and adherend stiffness, and the strength of certain adhesively-bonded butt and scarf joints. Hence evaluating $\lambda$ of

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$ (GPa)</th>
<th>$\sigma_0$ (MPa)</th>
<th>$t$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>3.4</td>
<td>36.5</td>
<td>0.396</td>
</tr>
<tr>
<td>SUS304</td>
<td>206</td>
<td>295</td>
<td>0.3</td>
</tr>
<tr>
<td>YH75 (ALU-alloy)</td>
<td>71</td>
<td>399</td>
<td>0.33</td>
</tr>
</tbody>
</table>
adhesive joints is of practical important, and this can be done via following calculation method as performed by Bogy [2].

4. Results and discussion

The stress multiaxiality in the central region of adhesive layer in scarf joints of various angle is shown in Fig.2. Obviously, for scarf joints considered (i.e. 45˚, 60˚ and 75˚) in this study, the stress states inside the adhesive layer are remarkably triaxial and the magnitude of tensile principal stresses increase with the inclining scarf angle. Figure 3 shows the effect of scarf angle on tensile stress of scarf joints. For scarf angle larger than 45˚, maximum principal stress is the dominant failure criteria.

Following the same procedure as Bogy as mentioned above, we have measured the λ of scarf joints under consideration and the results are plotted in Fig. 4. As can be seen, λ at an interface corner varies with the scarf angle and vanishes at a certain scarf angle. These results, at a glance, can be anticipated at which interface corner the scarf joint will fail. For example, at 45˚ scarf angle, λ exists at steel/adhesive interface corner but not at aluminium/adhesive interface corner. So, in this case, it can be predicted that the fracture will initiate at steel/adhesive interface corner. In fact, it was confirmed from fracture surfaces observations that fracture initiated at this point in almost all specimens tested.

Effect of bond thickness on apparent Poisson’s ratio of scarf joints is shown in Fig. 5. In the case of joints having scarf angle of 60˚ and 75˚, σ/thetahyd is almost constant. This indicates, as already shown in Fig. 3, that the failure of these scarf joints is satisfied by the maximum principal stress. However, according to Fig. 5, scarf joints of 45˚ is determined by Mises equivalent stress.

The apparent Young’s modulus of adhesive layer, E’adh can be measured by dividing the axial fracture stress, σ1, of scarf joints by the apparent strain of adhesive layer, ε’adh. Here, a correction is needed to deduce ε’adh from the strain obtained by strain gage, ε. This can be fulfilled by calculating:

$\varepsilon'_{adh} = \frac{\varepsilon}{t} \left[ \frac{1}{2} (L-t) \varepsilon' \sigma_{s} - \frac{1}{2} (L-t) \sigma_{s} \right]$  (7)

where, L is the length of strain gage. Thus, effect of bond thickness on apparent Young’s modulus of adhesive layer, E’adh is shown in Fig. 6. It has been established for relatively brittle adhesive, that E’adh is related to the Young’s modulus of bulk epoxy adhesive, Eadh as

$E'_{adh} = \left[ \frac{1-V_{adh}}{1-V_{adh}} \right] E_{adh}$  (8)

It is noted, by substituting Poisson’s ratio of bulk epoxy adhesive, νadh into Eq. (8), E’adh is approximately 2 times higher than Eadh and is also plotted in Fig. 6, together with the Eadh. Clearly, E’adh is higher than Eadh and is found to be affected by bond thickness of scarf joints wherein E’adh is gradually increased when the bond thickness decreases. The apparent Young’s modulus of adhesive layer in scarf joints was found to be 1.5-5 times higher than those of bulk epoxy adhesive, which obtained from tensile tests. This also suggests that the apparent Poisson’s ratio of adhesive layer, ν’adh is not always equals to νadh and changes with the bond thickness.

Effect of bond thickness on Poisson’s ratio of adhesive layer is shown in Fig. 7. This figure confirms that for thick adhesive bond (i.e. t>0.4 mm), ν’adh is lower than νadh and for thin adhesive bond (i.e. t<0.4 mm), ν’adh is greater than νadh. ν’adh varies across the bond thickness.

5. Conclusions

Stress multiaxiality of scarf joints significantly increases as the scarf angle increases. From analytical solutions, stress singularity exists most pronouncedly at steel/adhesive interface corner of joint having 45˚ to 75˚ scarf angle and this is in agreement with FE analyses and is confirmed by fracture observations wherein the fracture always initiated at this point. Mechanical properties of adhesive layer in scarf joints are found to be different from those of bulk epoxy adhesive.

6. References

Fig. 2 Stress multiaxiality in epoxy adhesive layer.

Fig. 3 Effect of scarf angle on tensile stress

Fig. 4 Order of stress singularity, λ at interface corner

Fig. 5 Effect of bond thickness on tensile stress

Fig. 6 Effect of bond thickness on apparent Young’s modulus

Fig. 7 Effect of bond thickness on apparent Poisson’s ratio