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Effect of Interference Fits on the Fatigue Lives of Bolted Composite Joints

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Abstract: The effect of interference fits on the fatigue lives of bolted composite joints is investigated by conducting mechanical tests. Static and fatigue tests are carried out on specimens made of carbon-bismaleimide composites joined together as double-lap single-bolt joints. The bolts having interference fits ranging of 0 (neat fit), 0.5%, 0.75% and 1% are performed. The results demonstrate the relationship between fatigue life and different values of interference fits. After the fatigue tests, non-destructive evaluation (NDE) and scanning electron microscope (SEM) are used to observe the damage of the surrender and surface of the hole. The test results show that the interference fitted specimens have improved fatigue life compared to the neat fitted specimen. The NDE and SEM results reveal that the damage degree of interference fitted specimen is weaker than that for the neat fitted one.
Key words: composite joints, mechanical testing, fatigue testing, fatigue life, non-destructive testing
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0 Introduction

Owing to their high strength-to-weight and stiffness-to-weight ratios, polymer composite materials have been widely used in aerospace and other engineering industries[1-2]. It is required for the composites to be jointed either to composites or to metals. And the mechanical fasteners are commonly used to form joints. Usually, there are three types of joints to be used in composite structures, namely, mechanically fastened joints, adhesively bonded joints, and hybrid mechanically fastened (adhesively bonded) joints[3]. It has been shown that many factors[4-7], such as joint geometry parameters, clearance or interference, clamping force, washer size, lay-up sequence, initial preload and type of joints (single-lap or double-lap), can influence the strength of the fastened joints.

Many studies have been made on the bearing strength and/or fatigue behavior of mechanically fastened joint in composite laminates[8-10]. Among those, the effects of joint geometry parameters (i.e. e/d and w/d ratios) on failure loads and models of double-lap single-bolt joints subjected to tension were investigated by Cooper and Turvey[11], where e is edge distance, w is width of the specimen and d is diameter of bolt-hole. Their experimental results showed that the failure loads depend directly on both e/d and w/d. The failure model changes from shear-out ($e/d < 3$) to bearing ($e/d > 3$) with the increase of e/d, while the failure model changes from net-tension ($w/d < 4$) to bearing ($w/d > 4$) with the increase of w/d. Xiao and Ishikawa[12] studied the strength and failure of mechanically fastened composite joints by means of scanning electron microscopy (SEM) at different loading levels to assess internal damage. Their observations indicated that the bearing failure can be outlined as a process of compressive damage accumulation. Bearing strength and failure model depend on the lateral constraints and the toughness of different polymer-matrix based laminates. Ascione et al.[13] studied the effects of forming techniques (such as fibre-to-load inclination angle and laminate stacking sequence) on the bearing load capacity of glass fibre/epoxy laminates. Their results showed that the bearing failure load is reduced when the fibre inclination angle is increased. Chen et al.[14] investigated the stress distribution surrounding the fastener hole on multi-bolt single-lap jointed sign in large-scale thick laminate multi-bolt joints by two-dimensional (2D) to three-dimensional (3D) global-local finite element method (FEM). The results showed that the stress distribution around the fastener hole is quite uneven in through-the-thickness direction, which is a useful criterion for further more complex studies involving failure analysis. Liu et al.[15] studied the effects of different assembly parameters, including the bolt clamping forces and the bolt-hole interference fit

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conditions, on the mechanical behaviors of the bolted composite joints under tensile loading. Liu[16] studied the effect of the liquid shim layer thickness on the mechanical behaviors of composite-to-titanium bolted joints using 3D FEM. They concluded that the maximum load, the initial joint stiffness and the design load of the joints decrease with the increase of the thickness of liquid shim layer. Besides, Croccolo et al.[17] investigated the axial tension in adhesively bonded and composite-steel compression fitted connections. They concluded that the external surface of the composite bush must be machined in order to produce some specific hoop channels for the adhesive hosting.

Bolted joints are the dominant fastening mechanisms used in jointing of primary structural parts[18-19]. Interference fit can be generally used to reduce the stress concentration factors and the magnitude of the local stress. In case of fatigue loading, the fatigue life of composite joints can be greatly improved by interference. However, there were few studies on the interference fit actions for the pin/hole and/or bolt/hole interference fit joints[20-23]. Hüyük et al.[24] examined the elastic-plastic interference fitted joints for pin-tube geometries through physical trials and numerical models. Their results showed that there are three distinct stages as the pin is pushed into the tube, and an optimum geometry maximizing the joint strength exists. Chakherlou et al.[25] investigated the effect of interference fit on fatigue life of holed plate of mechanical joints made of Al 7075-T6 alloy. The fatigue tests were conducted on an open hole specimen and the specimens with 1%, 1.5%, 2% and 4% nominal interference fit sizes at different cyclic longitudinal loads. Their results showed that interference fit increases fatigue life compared to the open hole specimen.

In the present work, an experimental study is carried out to investigate the static and fatigue behavior of bolted joints in composite laminates with different interference fit sizes. The surrender and the surface of the hole are estimated by non-destructive evaluation (NDE) and SEM. The effects of interference fit on mechanical properties are examined in detail.

1 Specimens and Experimental Investigation

1.1 Material and Specimen Preparation

A carbon fibre reinforced bismaleimide composite, referred to as T700/QY9611, is selected in the experimental studies. All of the specimens are cut from the composite laminates according to the mechanical tests. Each ply of the specimen has the same material properties which are listed in Table 1. The specimens are supplied by Chengdu Aircraft Design and Research Institute of China. The dimensions of a specimen are shown in Fig. 1. The specimen has a fastener hole with diameter of 8 mm. All of the specimens have the same values ($w/d = 5.5$ and $e/d = 5$), and the total specimen length is equal to 260 mm.

Table 1 Properties of the composite materials

Property	Value
Density/$(\mathrm{g \cdot cm^{-3}})$	1.57
Elastic modulus/GPa	128
Compress modulus/GPa	123
Tensile strength/GPa	2.91
Compress strength/GPa	1.25
Poisson's ratio	0.29

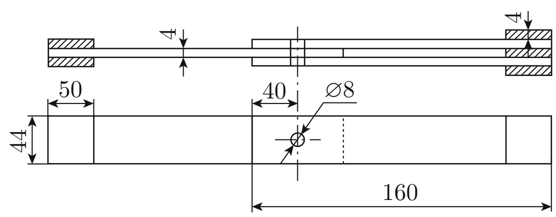


Fig. 1 Geometrical configuration of bolted joint specimen (mm)

1.2 Interference Fit Determination

The geometrical configuration of the joint setup is shown in Fig. 2. For the clamping-up of experimental machine, a filler plate made of aluminum alloy is used.

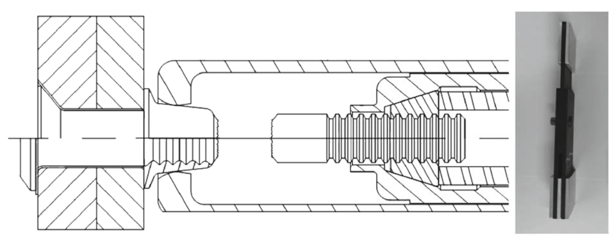


Fig. 2 Schematic of the assembly progress of blind bolt

Four sizes of interference fits, 0, 0.5%, 0.75% and 1%, are considered in the tests. The interference fit size can be expressed by

$$I = \frac{D - d}{D}, \tag{1}$$

where D is the bolt diameter.

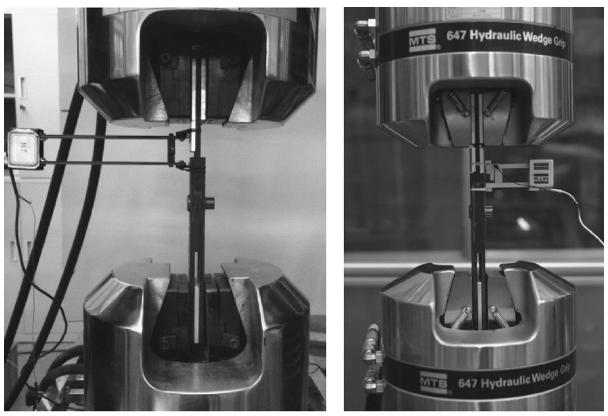
1.3 Failure Definition

The failure definition under fatigue loading is rather complex for a bolted joint. The best way of applying fatigue stress level is obtained from the static bearing strength. It is necessary to adopt a relatively simple way to monitor bearing damage during a fatigue test. The extensometer measuring system is used to determine the hole elongation. Generally, testing is not terminated until enough bolt-hole elongation (hole wear) is produced (it may be 4% deformation of hole diameter) or 3×10^6 cycles are achieved.

1.4 Test Procedures

The tests in this study are relatively easy to be performed, while on the other hand they give a realistic background for assessing the material combinations without losing any significant data. The static mechanical testing is carried out, and the bearing strength of different interference fit size joints is compared at the same time in order to obtain the ultimate bearing strength. The fatigue testing is used to provide the relationship between fatigue life and interference fit size.

Mechanical properties of the composites are determined experimentally at room temperature. ASTM D5961/D5961M-13 standard test method[26] for bearing response of polymer-matrix composite laminates is used to determine the ultimate bearing strength of polymer-matrix composite laminate specimens in double-shear tensile loading. Joint damage can be indicated through joint stiffness reduction or hole elongation (hole wear). Static bearing tests are performed by using MTS tensile test machine. Static tests are conducted under $(23 \pm 3)\,^\circ$C condition with 2 mm/min ramp speed. The test setup is illustrated in Fig. 3.



(a) Static testing (b) Fatigue testing

Fig. 3 The setup of a specimen

The static ultimate bearing strength is the value of bearing stress at the maximum load capability of a bearing specimen. This bearing stress can be expressed by

$$\sigma_{\text{ult}} = \frac{P_{\text{ult}}}{Dh}, \tag{2}$$

where P_{ult} is the ultimate load of the static testing, and h is the nominal thickness of the main laminates of bolted joints.

For the fatigue tests, the cycle loading applied to all specimens has a constant amplitude sine wave with a stress ratio of $R = -0.1$. Fatigue tests are conducted according to the ASTM D6873 standard[27] at a room temperature of $(23 \pm 3)\,^\circ$C. For each specimen group, the maximum of fatigue load is about 90% of the ultimate failure load of static test, while the minimum of fatigue load is about −10% of the ultimate failure load of static test. The temperature rise caused by relative motion between the joint parts is a major factor to be considered in the test. If the temperature rise becomes excessive, it may cause premature failure of the joint. Frequency of 5 Hz is selected to avoid this. In addition, a cooling fan with compressed air directed onto the bolt is implemented, and the temperature of the bolt is monitored with infrared thermometer. It should be noted that the temperature on the surface of the bolt is likely to be less than the temperature in the interior of the joint, the target maximum temperature for the bolt surface is set to be $60\,^\circ$C, and the test frequency is adjusted to maintain temperatures below this value. An extensometer is used in order to measure the bolt-hole elongation for the double-lap single-bolt joint specimens. Each test is repeated at least five times and the mean values are taken as test results under 95% confidence level.

1.5 Microstructure Characterization

The microscopy observation can give the information on void, delamination, fibre distribution and other damage situations. The following evaluation methods are chosen to compare the composite joints considered. Prior to and in specific intervals during fatigue testing, all specimens are inspected by using an acousto-ultrasonic device (Phasor XS by GE). This portable device is versatile and allows the detection of flaws which may be either debonding or delamination within the patch. However, the instrument does not provide information about the type of the defects. Consequently, only the extent and position of the defects are measured during inspection. This NDE instrument has A-scan, B-scan, C-scan and S-scan functions. The type of probe used in this test is phased array with 5 MHz frequency and 32 wafers which can detect the delamination, crack and so on.

In order to evaluate the extrusion damage of hole after fatigue testing, we use SEM to observe the surface morphology and fracture behaviors of composites. The SEM samples are coated with approximately 10—20 nm of gold before examination with a ZEISS-ULTAR PLUS apparatus. As the type of the failure mode (crushing/delamination) cannot be known after testing, the damage type of the specimens can be evaluated by this instrument.

2 Results and Discussion

2.1 Static Bearing Strength

Figure 4 presents typical load-displacement curves for three types of specimens. T700-1 is the specimen with blind bolt of neat fit. T700-2, T700-3 and T700-4 are the specimens with blind bolt of 0.5%, 0.75% and 1% interference fits, respectively. The definition of static failure is defined when the maximum load is achieved during the test. The test results show that the ultimate bearing load of T700-3 group with 0.75% interference fit is 42 kN, and it is about 10.5% higher than that of T700-1 group. The ultimate bearing load of T700-2 group is 40 kN, and it is about 5.3% higher than that of T700-1 group. The ultimate bearing load of T700-4 group is 41 kN, and it is about 7.8% higher than that of T700-1 group. It is found that the proper interference fit can increase the ultimate bearing load of composite joints, while excessive interference fit decreases the ultimate bearing load. However, although the ultimate bearing load of the specimen varies with the size of interference fit, the same nominal maximum bearing load ($\sigma_{\text{ult}} = 2.386\,\text{GPa}$) is taken in order to obtain better comparison of fatigue results.

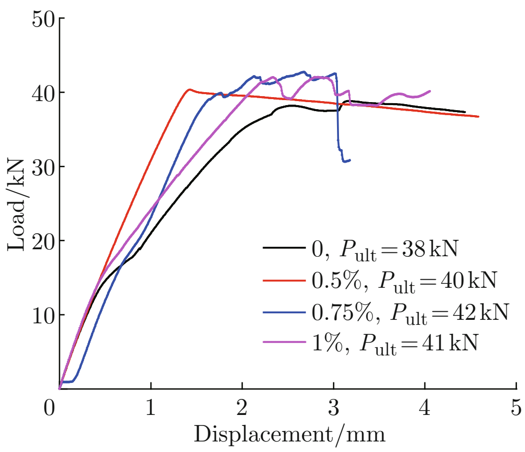


Fig. 4 Load-displacement curves for three types of specimens

2.2 Fatigue Life

All tests are made with double-lap joints under fatigue loading of 0.1 stress ratio. Tests are load-controlled in sinusoidal wave at 5 Hz frequency adjusted to limit specimen surface temperature below 60 °C. The test results show that the bolt-hole elongation increases with the increase of the number of fatigue cycles. Through the typical hysteresis load-displacement plots, the clearance can be observed after several fatigue cycles. After the gap between bolt and hole appears, the bolt which impacts the hole wall under tension and compression cyclic loading may cause the impact damage around the connecting hole in composite laminates. When the gap is sufficiently larger, the impact damage becomes more serious so that the gap reaches to the failure value of specimens. For the joint with interference fit, when the fastener is closely contacted with the connecting hole, the impact damage caused by dynamic loading may largely delay. Fatigue tests are not prevented until the bolt-hole elongation reaches the requirement of 4% of the hole diameter.

Fatigue lives of bolted joints with four interference fits, 0 (neat fit), 0.5%, 0.75% and 1%, are obtained. There are 6 specimens for each interference fit. The average value of each case meets the 95% confidence level. Typical results for these four cases are listed in Table 2. Selecting the appropriate size of interference fit can greatly improve the fatigue properties of composite bolted joints. From Table 2, it can be clearly seen that T700-3 group with 0.75% interference fit has the highest fatigue life among the four cases. The fatigue life is reduced whenever the interference fit is higher or lower than 0.75%.

Table 2 Fatigue lives with four sizes of interference fit

Serial number	Interference fit/%	Specimen numbers	Fatigue life$\times 10^{-3}$
T700-1	0	6	45.520
T700-2	0.5	5	97.769
T700-3	0.75	5	241.576
T700-4	1	6	51.663

The compressive residual stress caused by the interference join can reduce the stresses near the hole edge. Meanwhile, the delamination phenomenon at the hole edge is found, and the stress concentration is decreased. Therefore, the load bearing and fatigue life may be improved.

The results show that the bolted joint with interference fit improves the fatigue life, and the important factors in designing composite bolted joint not only include the static ultimate bearing strength of composite materials and the size of interference fit, but also include the stress level at which the bolted joints are generally applied.

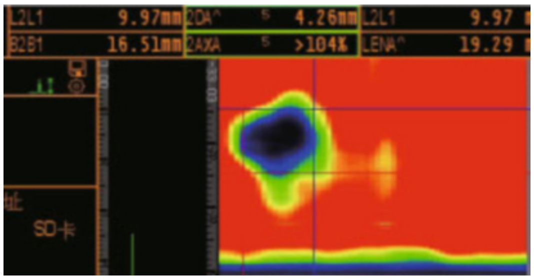
2.3 NDE

The specimen damage situation is evaluated by NDE after fatigue life testing in order to observe what type damage occurs during fatigue load cycling. Typical results of NDE measurement are shown in Fig. 5. It can be seen that the bolt-hole elongation has a different size under these four cases. It might also be noted that the sizes of the bolt-hole elongation provided by NDE instrument are just relative values which can be compared with each other. The percentage of hole damage is defined by

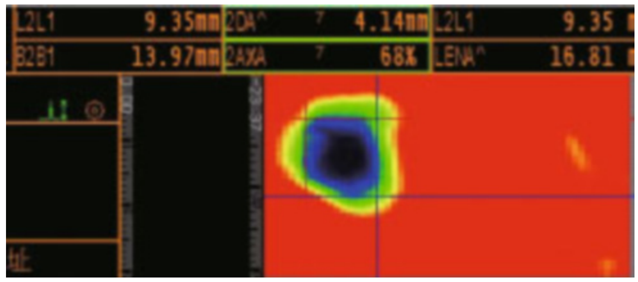
$$\eta = \frac{D' - D}{D}, \tag{3}$$

where D' is the bolt-hole diameter measured by NDE after fatigue testing.

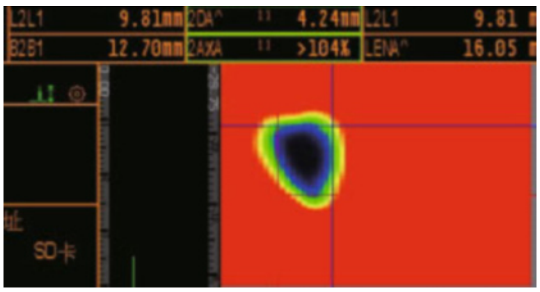
The percentage of hole damage with different interference fits is measured and plotted in Fig. 6. The results show that the percentage of hole damage is reduced from 90% to 50% when the interference fit is increased from 0 to 0.75%. The percentage of hole damage reaches 140% when the interference fit is 1%.



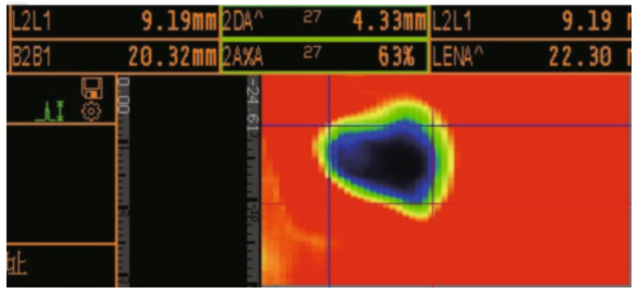
(a) 0 interference fit



(b) 0.5% interference fit



(c) 0.75% interference fit



(d) 1% interference fit

Fig. 5 NDE pictures on the surrender of the hole

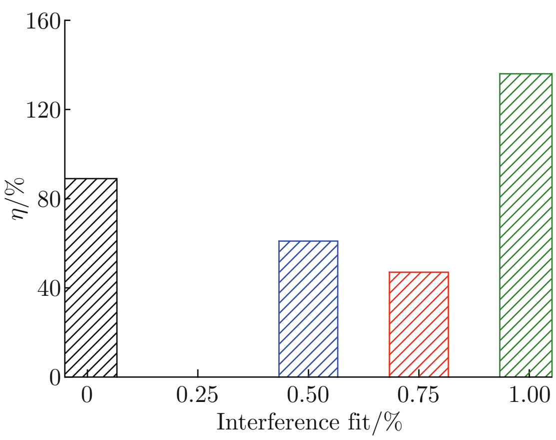


Fig. 6 Percentage of hole damage with different interference fits

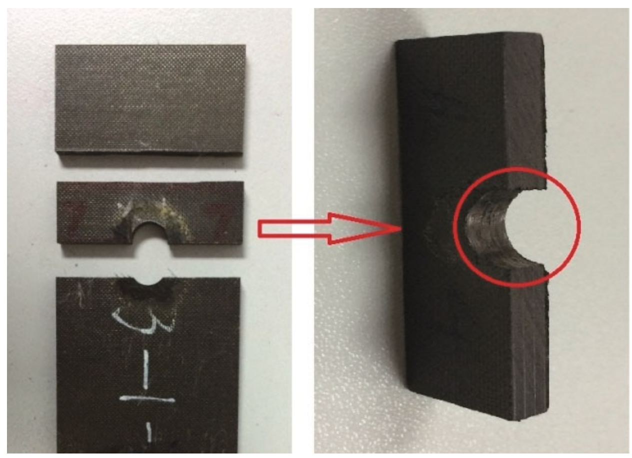
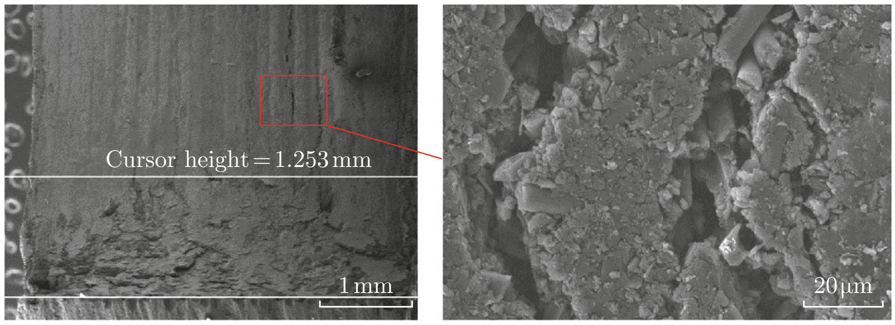


Fig. 7 Picture of specimen for SEM observation

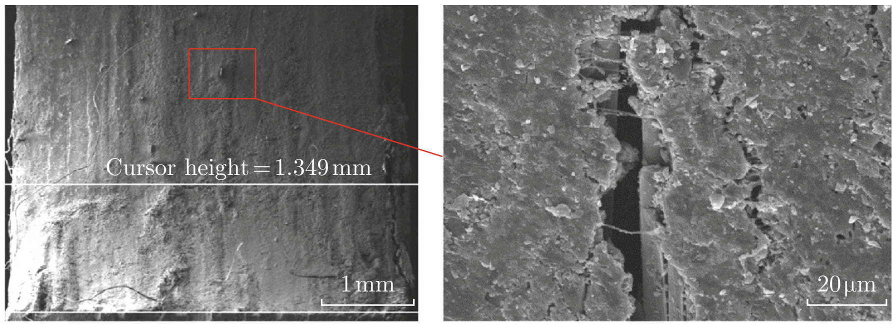
2.4 Microstructure

In order to observe the internal damage in detail, some specimens are cut along the centerline after the fatigue tests described in the previous sections. SEM images are taken on the surface extrusion sections of the hole with 0, 0.5%, 0.75% and 1% interference fits, respectively. The observing area is shown in Fig. 7. Figure 8 shows SEM micrographs of the fractured hole surfaces around the extrusion zones after the fatigue tests. Pictures on the left of Fig. 8 show the crushing sizes of hole. The crushing degree is terrible with 0 interference fit and it becomes much bad with 1% interference fit. The crushing size is reduced when the interference fit is increased, and the crushing size with 0.75% interference fit is the smallest.

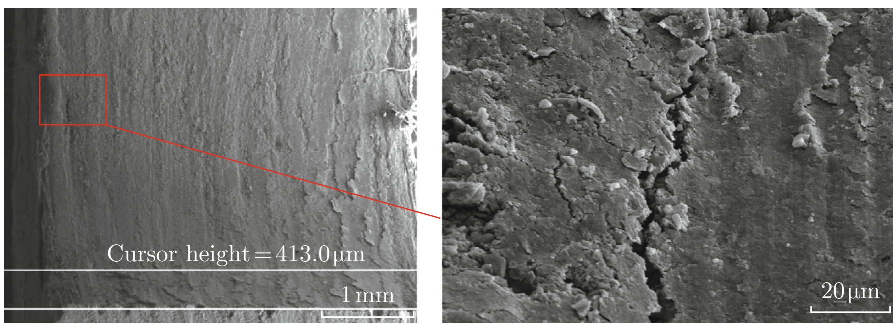
The main damage phenomenon in region is crushing, crack or surface damage occurring in the contact region between the bolt and the hole. Pictures on the right of Fig. 8 show the crack sizes with different interference fits. They are the local area magnification of the left pictures. The crack is wider than that of other interference fitted specimens, and there are crushing fibers surrendering the crack under no interference fit. The crack is reduced when the interference fit is increased. However, the crushing area becomes larger when the interference fit is further increased. The oversize interference fit may cause extruding stress and the abrasion may occur when the fatigue load is applied. The reaction force acting on the hole surface can be increased as a result of the bolt bending deformation.



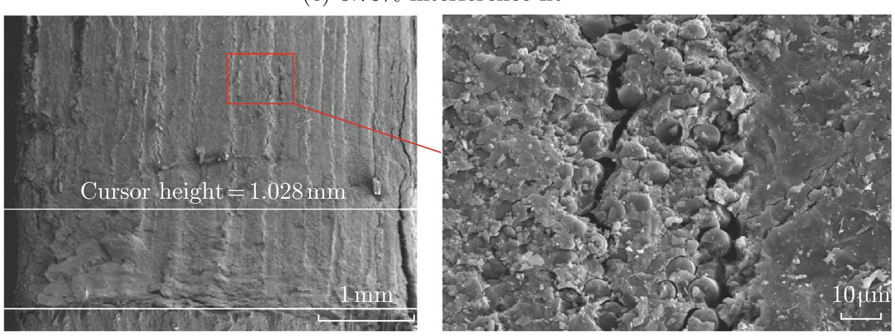
(a) 0 interference fit



(b) 0.5% interference fit



(c) 0.75% interference fit



(d) 1% interference fit

Fig. 8 SEM images of surfaces of the hole extrusion zones

3 Conclusion

The interference fit actions have been investigated in the experimental studies. Compared to the neat fitted specimen, the interference fitted specimens have improved the fatigue life. The fatigue life of the interference fitted specimens is increased when the interference fit is increased from 0.5% to 0.75%. In contrast, the fatigue life of the specimen with 1% interference fit is lower than that of the same specimen with 0.75% interference fit. The NDE results reveal that the damage extent becomes small when the interference fit is increased, but it decreases with further increase of the interference fit. The SEM observations reveal the two main damage behaviors of the hole surrender and surface. The damage degree of interference fitted specimens is weaker than that for the neat fitted one.

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