Double-shear behavior of the bolted joint connecting C/SiC plates

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1 Introduction

Thermal Protection System (TPS) is usually covered on the surface of the aircraft as the thermal protecting layer. Owing to the complex shape and structure of the aircraft, a unibody design and manufacture of TPS is infeasible, therefore it is unavoidable to connect lots of thermal protection components. Consequently, heat shorts arising from the gap and joints between thermal protection components cannot be ignored [1]. Heat shorts may lead the interior part of the fuselage structure to an extreme high temperature, severely degrading the heat insulation property of the TPS. In the process of service, the TPS has to bear not only thermal loads, but also mechanical loads as well as harsh chemical environments, repeatedly without failure [2]. Therefore, in the study of the TPS, the analysis of heat shorts effect and the use of high temperature resistant joints with high strength are indispensable. Much work has been done to join ceramics and ceramic matrix composites, including brazing [3-4], diffusion welding [5] and precursor infiltration [6], however, the joining strength is still not enough to satisfy the requirement in aerospace application. The mechanical joining by the introduction of bolts can satisfy the joining strength at moderately high temperature, but most researches focused on metal joints [7-9], whose heat insulation properties are quite poor, and rare studies have been done on heat shorts blocking joints. Some efforts have been done on C/SiC joints [10-11], yet the complicated fabrication approaches for geometrically complex composites such as bolted joints have certain limitations in terms of size and shape, which have greatly limited their wider applications. The studies for multifunctional bolted joints with load bearing-heat insulation integration which are quite necessary for joints used on TPS are less. Functionally graded materials (FGMs) are ideal candidates for the applications requiring multifunctional performance. For instance, the metal-ceramic FGMs can be designed to take advantages of the mechanical strength of metals and the heat and corrosion resistance of ceramics [12-13]. In our previous study, we fabricated and experimentally investigated the microstructure and thermomechanical properties of the porous ZrO2/(ZrO2+Ni) FGMs and found that they had a low thermal conductivity and high strength [14-15]. Therefore, the metal-ceramic FGMs can be a potential candidate for heat shorts blocking joints. Finite element analysis (FEA) has been widely used to analyze the thermal and mechanical properties of the joints [16-18], since the method through experimental study to obtain the properties of the metal-ceramic functionally graded bolted joint (FGBJ) is accurate but time-consuming, so the theoretical simulation and optimization would be rather important for the successful implementation of metal-ceramic functionally graded jointing technology in a wide variety of application. In this paper, firstly a new kind of the Thermal Protection System used metal-ceramic functionally graded bolted joint (FGBJ) is prepared, whose material system (porous ZrO2/(ZrO2+Ni) FGMs) is fabricated by cold isostatic pressing and pressureless sintering (CIP-PLS). Microstructures and mechanical properties of the FGMs are experimentally studied in our previous work [14-15]. Then the damage mode and fracture load of the bolted joint connecting plates are investigated by simulating the double-shear behavior of the bolted joint. Finally the shear band (ZrO2+VNi of thickness h, V is the volume fraction) is introduced to the shearing face of the bolted joint to improve its shearing strength, structural design is done and the optimal shear band is proposed to balance the shearing strength and heat insulation performance of the bolted joint. The findings will highlight the optimization of the structure of the multifunctional bolted joint with load bearing-heat insulation integration.

2 Bolted joint preparation

We have fabricated porous ZrO2/(ZrO2+Ni) functionally graded samples in our previous work [14], as shown in Fig. 1a. The height of the bearing load layer (layer a, 12 porosity), transition layer (layer b, 15 porosity) and middle layer (layer c, 30 porosity) are ha=10mm, hb=2mm, and hc=10mm in the axial direction, respectively. These samples are to be further manufactured into the functionally graded bolted joints. Fig. 1b shows the materials and structure of the bolted joint. The bolt thread, bolt head and nut are all composed of the bearing load layer (ZrO2+30vol. Ni) to ensure the mechanical strength and service reliability. The bolt shank without threads mainly consists of the middle layer (ZrO2), which serves the purpose of heat resistance. The transition layer (ZrO2+15vol. Ni) on the bolt shank is designed to reduce the residual stresses which are generated inevitably due to the mismatch in coefficients of thermal expansion between different layers. The transition layer also fulfills the function of cutting the fillet. According to the standard handbook of fastening and joining [19], the diameter and height of the bolt head are s=12.8mm and k=5.5mm, respectively. The diameter of the bolt shank is D=7.8mm, which is also the major diameter of the external thread. The height and diameter of the nut are m=6mm and s=13mm, respectively. The thread pitch is P=1.25mm, then the number of engaged threads on the nut is thus calculated to be five. In this study, the number of threads is not a significant factor because the bolt is mainly subjected to the shearing load perpendicular to the axis, rather than the axial load.

3 Finite Element Modeling

To study the shearing properties of the bolted joint, a three-dimensional (3D) finite element model of the double-shear bolted joint connecting plates is constructed based on ABAQUS code, as illustrated in Fig. 2. The error resulting from neglecting the helix angle is ignored in this study, since the helix angle is very small (less than 2 deg) on most bolts. As illustrated in Fig. 2a, the hole diameter (D) is 7.8mm, the plate length (L), width (W), and edge distance (Ed) are 7D, 6D and 3D, respectively. This is to avoid the tensile and edge shearing rupture of the plate, which usually happen when ratios of width to diameter (W/D) and edge distance to diameter (Ed/D) are less than three. These two damage modes make the bolted joints fail to bear loads catastrophically even under little mechanical loading and should be avoided in practical application. The only difference between the upper, middle and lower plates is their thicknesses, which are 4mm, 6mm and 4mm, respectively. Since the bolt is mainly subjected to the shearing load perpendicular to the axis rather than the axial load, the number of threads is not a significant factor. Only the fully engaged part of the nut and bolt are included in the finite element model, while threads without engagement are neglected. The model consists of 113528 elements with 128690 nodes, as shown in Fig. 2b. The C3D8R elements are used for the explicit dynamic analysis based on ABAQUS nonlinear finite element codes. The total time period of the dynamic analysis is 0.01s. Contact is defined between all the contacted surfaces. The friction coefficient of bolted joints usually ranges from 0.2 [20], and thus the same friction coefficient 0.15 is adopted here between all the contacted surfaces. The boundary condition is fixing the left surfaces of the upper and lower plates, while applying displacement (1mm) to the right surface of the middle plate. are listed in Table 1-2 [21-22], and correspond to the equivalent fracture strain at shear damage initiation for equibiaxial tensile and equibiaxial compressive deformation, respectively. The shear stress parameters and correspond to the values of for equibiaxial tension and compression respectively, with and . Here is a constant parameter and is taken as 0.3 in ABAQUS. should be in accordance with the finite element model, which is 1/0.01s. When these three parameters are determined, the equivalent fracture strain at the onset of damage for each kind of material can be obtained. The shear-damage model parameters used are shown in Table 4.

4 Results and Discussion

4.1. Damage mode and fracture load of the bolted joint connecting plates Due to the high ratios of width to diameter (W/D) and edge distance to diameter (Ed/D), the tensile and edge shearing rupture of the plate are impossible to occur during the loading process. There are two possible damage models including the extension damage of hole surface of the plate and the shearing damage of the bolt. Fig. 3(a)-(c) show the Mises stress contour and morphology of the bolted joint at different loading stages. The load-displacement curve of the loading end (right surface of the middle plate) during the whole loading stage is shown in Fig.3(d), which is obtained by extracting the reaction force-time curves of the fixing ends (left surfaces of the upper and lower plates) and the displacement-time curve of the loading end. We can see that there are three obvious different stages in the load-displacement curve, which is in accordance with the three loading stages shown in Fig. 3(a)-(c): (a) Initial elastic deformation stage, this stage lasts until the external load reaches its peak value (4400N), which is also the fracture load. (b) Initial damage evolution stage, the external load gradually decreases and reaches a near zero value when the displacement of the loading end of the middle plate increases to 0.4mm. This stage is relatively short, meaning that attenuation of load bearing capacity of the bolt after reaching the shearing strength is fast. (c) Later damage evolution stage, the external load decreases to zero which means the bolted joint has totally been fractured. Therefore, the damage mode of the bolted joint connecting plates is the shearing damage of the bolt. Moreover, the shearing failure faces are layered rather than smooth, as shown in Fig. 3(c). This phenomenon illustrates that when the crack propagates to a certain length, almost half of the diameter of the bolt according to the result in Fig. 3(c), the two shearing faces of the bolt are not subjected to the pure shearing load any more, which makes the crack deflection or bifurcation happen. 4.2. Effects of the shear band on heat insulation property of the bolted joint To improve the shearing strength of the bolted joint, we introduce the ductile shear band (ZrO2+VNi of thickness h, V is the volume fraction of Ni) to the shearing faces of the bolt, as shown in Fig. 4. It should be noted that after adding the ductile shear band, the thermal conductivity of the bolted joint will increase since the thermal conductivity of ZrO2 mixed with Ni is greater than that of ZrO2 in the previous shearing faces, as listed in Table 1. To study the effects of the shear band on heat insulation property of the bolted joint, we firstly compute the equivalent thermal conductivity of the bolted joint along the height direction. The corresponding equivalent heat resistance schematic is shown in Fig. 5. By Fourier's law of heat conduction, the equivalent thermal conductivity of the bolted joint along the height direction can be approximately calculated as [28]: where H, A are the equivalent height and cross-sectional area of the bolted joint correspondingly, R is the equivalent heat resistance. The heat resistance Ri of each layer is given by where , , are the height, cross-sectional area and conductivity of each layer, respectively. The equivalent model of the whole bolted joint can be assumed as the series model. The equivalent heat resistance R and equivalent height H can then be given by Combing Eqs. (4)-(6), the equivalent thermal conductivity along the height direction is express as different Ni volume fractions (V) and thicknesses (h). We can see that the equivalent thermal conductivity increases with the increase of Ni volume fraction and thickness of the shear band. When the Ni volume fraction is less than 20, the effects of the thickness of the shear band on the equivalent thermal conductivity is rather limited. Also, when the thickness is no greater than 2mm, the effects of the Ni volume fraction of the shear band on the equivalent thermal conductivity is not obvious. The maximum equivalent thermal conductivity of the bolted joint under these two circumstances are less than 1.6, which is only slightly greater than that of the bolted joint without the shear band. This result will be combined with the following section concerning the effects of the shear band on load bearing property to optimize the structure of the bolted joint. 4.3. Effects of the shear band on load bearing property of the bolted joint Firstly we study the effects of the Ni volume fraction (V) of the shear band on load bearing property of the bolted joint. The thickness (h) of the shear band is fixed at 2mm, three different cases are simulated for the bolted joint with the shear band: (i) V=15, (ii) V=30, (iii) V=45. The minimum Ni volume fraction is 15 considering that the minimum Ni volume fraction of the mixture of $ZrO2$ and Ni is 15 (transition layer, $ZrO2$+15vol. Ni) in the original bolted joint without the shear band. Material properties and damage evolution parameters used can be seen in Table 4. Fig. 7(a)-(c) show the Mises stress contour and morphology of the bolted joint with the above three different Ni volume fractions at the end of the loading stage. The corresponding load-displacement curve of the loading end (right surface of the middle plate) during the whole loading stage is shown in Fig. 7(d), the one without the shear band is also plotted as comparisons. As shown in Fig. 7(d), the fracture load increases as the Ni volume fraction increases, and the attenuation of the load bearing capacity after reaching the shearing strength also slows down. From our previous work [14], we have known that the porosity of the mixture of $ZrO2$ and Ni decreases as the Ni volume fraction increases. So the modulus and shearing stiffness of the shear band increase as the Ni volume fraction increases. Also, the equivalent fracture strain at damage initiation of the shear band increases as the Ni volume fraction increases, as shown in Table 4. The increment of both the modulus and the equivalent fracture strain at damage initiation of the shear band make the fracture load increase. But the increase is rather limited when the Ni volume fraction is greater than 15. To further investigate the effects of the Ni volume fraction on mechanical properties of the bolted joint, effects of the Ni volume fraction on the maximum thermal stress resulting from the mismatch of coefficients of thermal expansion between different layers of the bolted joint is plotted in Fig. 8. The specific method of computing the thermal stress can be seen in our previous work [21]. We can see that as the increase of the Ni volume fraction, although the increase of the thermal conductivity is rather limited (seen in Fig. 6), the increase of the maximum thermal stress is great. Therefore, the proper Ni volume fraction of the shear band is 15Then we study the effects of the thickness (h) of the shear band on load bearing property of the bolted joint. The Ni volume fraction (V) of the shear band is fixed at 15, three different cases are simulated for the bolted joint with the shear band: (i) h=2mm, (ii) h=3mm, (iii) h=4mm. The minimum thickness is 2mm considering that the minimum thickness of the mixture of $ZrO2$ and Ni is 2mm (transition layer, $ZrO2$+15vol. Ni) in the original bolted joint without the shear band, also with the consideration that the processing craft is complex when the thickness is less than 2mm. The Mises stress contour and morphology of the bolted joint with the above three different thicknesses at the end of the loading stage are illustrated in Fig. 9(a)-(c). Fig. 9(d) shows the corresponding load-displacement curve of the loading end (right surface of the middle plate) during the whole loading stage, the one without the shear band is also plotted as comparisons. As shown in Fig. 9(d), the fracture load increases as the thickness of the shear band increases to 2mm, and the attenuation of the load bearing capacity after reaching the shearing strength also slows down. However, when the thickness of the shear band is greater than 2mm, the effects of the shear band on load bearing property of the bolted joint is not obvious. Considering that the thermal conductivity of the bolted joint increases with the thickness of the shear band, the proper thickness of the shear band is 2mm. Therefore, the optimal shear band could be ZrO_2+15vol. Ni which is 2mm in thickness to balance the shearing strength and heat insulation performance of the bolted joint studied in this work.

5 Conclusions

A new kind of the Thermal Protection System used bolted joint made up of porous ZrO_2/(ZrO_2+Ni) is prepared. Double-shear behavior and fracture load of the bolted joint connecting plates is numerically analyzed in detail by ABAQUS codes. From the numerical simulations some conclusions can be drawn: (1) Shearing damage of the bolted joint occurs at the two shearing faces of the bolt when neglecting the tensile and edge shearing rupture of the plate which make the bolted joints fail to bear loads catastrophically even under little mechanical loading, and the shearing failure faces are layered rather than smooth. (2) The addition of the shear band to the shearing faces of the bolt can improve its shearing strength and slow down the attenuation of load bearing capacity after reaching the shearing strength, while it to improve thermal conductivity of the bolted joint is very limited. (3) The optimal shear band is proposed as ZrO_2+15vol. Ni which is 2mm in thickness to balance the shearing strength and heat insulation performance of the bolted joint studied in this work.

6 References

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