Composite Structures 134 (2015) 680–688

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Load distribution in threads of porous metal–ceramic functionally graded composite joints subjected to thermomechanical loading

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ARTICLE INFO

Article history:
Available online 3 September 2015

Keywords:
Functionally graded composite joints
Thermomechanical
Finite element modeling
Load distribution

ABSTRACT

Metal–ceramic functionally graded materials (FGMs) have been extensively used in aerospace engineering where high strength and excellent heat insulation materials are desired. In this paper, load distribution in threads of the Thermal Protection System used bolted joint made up of porous $ZrO_2/(ZrO_2 + Ni)$ FGMs is investigated by ABAQUS codes. The bolted joint is subjected to reentry heating corresponding to the Access to Space Vehicle. Effects of bolt–nut parameters including thread tooth profile, thread pitch, and modulus ratio of bolt to nut on load distribution in threads are analyzed in detail. It is found that uneven load distribution in threads occurs at elevated temperature, which mainly focuses on the first two threads closest to the nut bearing surface, with the first thread carrying 74% of the total load. Bolt–nut parameters have great effects on load distribution in threads, with trapezoidal thread, extra fine thread and greater modulus ratio of bolt to nut leading to more evenly distributed load. Further studies show that nut shape has significant effects on load distribution in threads, the optimized nut is designed to make the maximum load bearing ratio of the thread decrease to 30.21%, and thus the service reliability of the bolted joint is greatly improved.

1. Introduction

Thermal Protection System (TPS) has been widely used as the thermal protecting layer which is usually covered on the surface of the aircraft. Because of the complex structure and shape of the aircraft, a unibody design and manufacture of TPS is infeasible, therefore it is inevitable to connect lots of thermal protection components. Consequently, heat shorts resulting 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 damaging the heat insulation property of the TPS. During the process of service, the TPS has to withstand not only thermal loads, but also mechanical loads as well as harsh chemical environments, repeatedly without failure [2]. Therefore, in the research of the TPS, the analysis of heat shorts effect and the use of high temperature resistant joints with high strength are indispensable.

Many researches have been conducted on metallic thermal protection system, including the design and characterization of thermal insulation material/structure [3–8], however, rare studies have been done on heat shorts blocking joints. In addition, most researches focused on metal joints [9–15], which had quite poor heat insulation properties. Some studies were carried out on C/SiC joints [16–18], 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 the thermodynamic properties of these joints 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 example, the metal–ceramic FGMs can be designed to take advantages of the mechanical strength of metals and the heat and corrosion resistance of ceramics [19,20]. In our previous work, we fabricated and experimentally investigated the microstructure and thermomechanical properties of the porous $ZrO_2/(ZrO_2 + Ni)$ ceramics and found that they had a low thermal conductivity and high strength [21,22]. Therefore, the ceramic–metal FGMs can be a potential candidate for heat shorts blocking joints. Most of the bolted joints have uneven load distribution in threads, which are destined to affect the mechanical property and service reliability of the joints. Studies have shown that failure in threads are the most common failure mode of the bolted joint when subjected to axial tensile load [16,23]. This failure mode

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http://dx.doi.org/10.1016/j.compstruct.2015.08.113
0263-8223/

makes the strength of the bolted joint become less fully utilized. So the load distribution in threads is an important factor that cannot be neglected. However, few studies have been reported to date on the load distribution in threads of the bolted joint under thermomechanical circumstances. Therefore, it is of great importance to study the load distribution in threads of porous ZrO_2/(ZrO_2 + Ni) functionally graded bolted joint (FGBJ) subjected to thermomechanical loading, as well as the factors influencing the load distribution. Finite element analysis (FEA) has been widely used to analyze the thermal and mechanical properties of the joints [24–26], since the method through experimental study to obtain the thermomechanical 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 high temperature application.

In this paper, firstly a thermomechanical coupled finite-element (FE) model is constructed to study the load distribution in threads of the metal–ceramic functionally graded bolted joint (FGBJ), whose material systems (porous ZrO_2/(ZrO_2 + Ni) FGMs) are fabricated by cold isostatic pressing and pressureless sintering (CIP–PLS). Microstructures and mechanical properties of the FGMs are experimentally studied in our previous work [21,22]. Then load distribution in threads of the FGBJ with different bolt–nut parameters including thread tooth profile, thread pitch, and modulus ratio of bolt to nut are investigated, thus the optimized bolt–nut parameters are proposed for the FGBJ. Finally the optimal structural design of the bolted joint under thermomechanical circumstances is done to reduce the unevenly distributed load, and thus the service reliability of the bolted joint is also improved. The findings will highlight the optimization of the bolt–nut parameters and the structure of the bolted joint in a wide variety of high temperature application.

2. Preparation of the bolted joint

In our previous work [21], we have fabricated porous ZrO_2/(ZrO_2 + Ni) functionally graded samples, 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 l_a = 10 mm, l_b = 2 mm, and l_c = 10 mm in the axial direction, respectively. These samples are to be further manufactured into the functionally graded bolted joints. Fig. 1b shows the schematic of the bolted joint. The bolt head, bolt thread and nut all consist of the bearing load layer (ZrO_2 + 30 vol.%Ni) to ensure the mechanical strength and service reliability. The bolt shank without threads is mainly comprised of the middle layer (porous ZrO_2), which fulfills the function of heat resistance. The transition layer (ZrO_2 + 15 vol.%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. Also, the transition layer can serve the purpose of cutting the fillet. According to the standard handbook of fastening and joining [27], the height and diameter of the bolt head are k = 5.5 mm and s = 12.8 mm, respectively. The diameter of the bolt shank is d = 7.8 mm, which is also the major diameter of the external thread. The height and diameter of the nut are m = 6.8 mm and s = 13 mm, respectively. The thread pitch is P = 1.25 mm. The number of engaged threads on the nut is thus calculated to be five. The root radius of the thread is taken to be $L/6$, where L is the thread height. The bolted joint with the preload is called high-strength bolt, which usually needs only 2–3 threads out of the nut when the bolt and nut are fully engaged. Therefore, we suppose the number of threads on bolt shank is eight, and the height of the bolt shank with threads is accordingly to be b = 10 mm.

3. Theoretical simulation method

3.1. Finite element modeling

Based on ABAQUS codes, a two-dimensional (2D) axisymmetric finite element model is established using the advantage of symmetry, as shown in Fig. 2, to study the load distribution in threads of the bolted joint subjected to thermomechanical loading. The error caused by neglecting the helix angle and modeling the bolt and nut axisymmetrically has been ignored in this study, since the helix angle is quite small (less than 2 deg) on most bolts and thus the three-dimensional effect can be neglected. Actually, using 2D approximation for such a problem was also reported in the earlier experimental photoelastic studies [28]. This model comprises 48,147 elements and 48,976 nodes. The finite element mesh at the crest and root of the thread is refined using a very small element length. To improve the convergence, nodes between two mutually contacted threads are coincident. The thermomechanical response of the bolted joint is acquired with two steps. Firstly, heat transfer is simulated to obtain the time-dependent temperature distribution of the bolted joint subjected to the applied thermal loads and boundary conditions. Then, the load distribution in threads

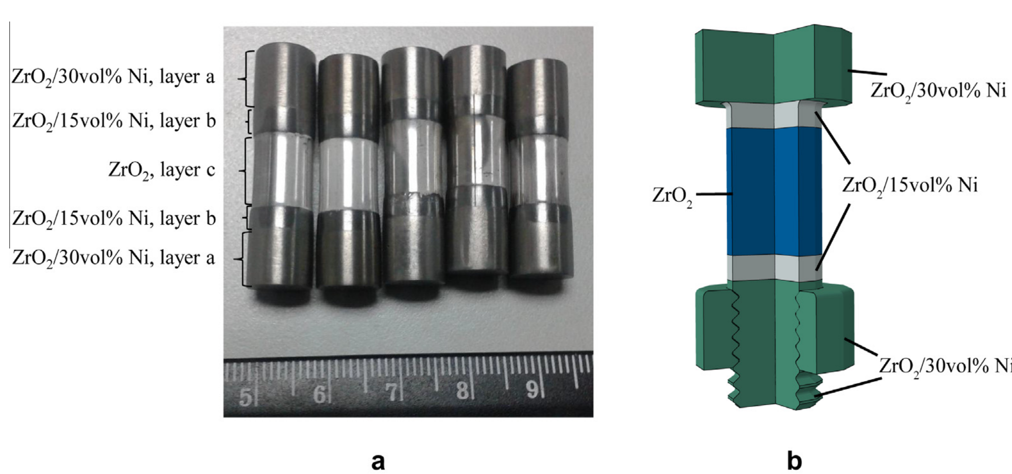

Fig. 1. (a) Optical photograph of the fabricated porous ZrO_2/(ZrO_2 + Ni) FGMs. (b) Materials and structure of the functionally graded bolted joint.