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Research Paper

Brazed residual stress in a hollow-tube stacking: Numerical simulation and experimental investigation

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ABSTRACT

In this study, the residual stresses of a hollow-tube stacking made of 316L stainless steel by brazing technology have been analyzed by finite element method and X-ray diffraction method. The results show that simulated results are in good agreement with the experimental data, reflecting the feasibility of finite element method to calculate the residual stress. Large tensile stresses are generated in the brazing filler metal, decreasing the cooling rate can decrease the residual stress. With the tube diameter, brazing filler metal thickness increasing, or tube length decreasing, the residual stresses in the filler metal decrease. Increasing the wall thickness can decrease the transverse stress at the middle region of the brazing filler metal, while it can increase the longitudinal stress at the vicinity of brazing fillet. The matrix size of the hollow-tube stacking has little effect on the stress distribution of the 316L/BNi-2 brazed joint. When the tube diameter is increased to 8 mm, the residual stress in the fillet transforms into compressive stress and thus can decrease the cracking sensitivity in the fillet. It is proposed that the diameter of tube should not be less than 8 mm from the viewpoint of generating compressive stress.

1. Introduction

Hollow-tube stacking, a kind of cellular structure, is very promising as lightweight aeronautical frames since it has superior specific mechanical properties such as structural or impact resistance [1,2]. The core of the hollow-tube stacking is fabricated by the brazing technology, and plenty of brazed joints are generated between the hollow-tubes. For many metallic cellular materials, a lot of cracks will be generated in the brazed joints, which named as node failure. Sun and Gao [3] studied the mechanical behaviour of a composite pyramidal truss core sandwich panel. The results indicate that two kinds of failure modes are observed in the sandwich panel: the strut fracture and node rupture. Xiong et al. [4] also found that the node failure and the strut buckling are the main failure modes for carbon fiber pyramidal truss sandwich panel. There are mainly two reasons are generalized for the node failure. One is that the deformation of strut leads to the stress concentration at the node due to the geometrical discontinuity. In order to decrease this type of stress concentration, Queheillalt [5] proposed a liquid interface diffusion bonding approach to form a large fillet between the truss and face-sheet interface, which is helpful to decrease the stress concentration and increase the interfacial strength. Jiang et al. [6] also found that a larger fillet can decrease the stress concentration and increase the tensile strength for brazed plate-fin structure. The other reason is that the brazed residual stresses generated by the mismatching of mechanical properties between the brazing filler metal and substrate metal [7]. The brazed residual stresses have a great effect on the structure fracture [8–10] and buckling [11–13]. Therefore, it is very important to decrease the brazed residual stress for ensuring the structure integrity.

The brazing filler metal is surrounded by the base metal, the whole brazed joint like a kind of sandwich structure. The thickness of brazing filler metal is only about 30–100 μm, while the thickness of base metal is several millimeters or even more thick. Therefore, it is a challenging question to measure the residual stress accurately in the brazed joint, especially for the stress characterization of the brazing filler metal. X-ray diffraction (XRD) [14,15] and neutron diffraction method [16] are widely used to measure the residual stress. Although the XRD cannot measure the inner stress of the brazed joint directly limited by the penetrate capability [17], stress gradients can be characterized in combination with the layer removal by electrochemical polishing technique. Neutron diffraction can penetrate into the material and test the residual stress directly due to the higher penetrate capability. However, it is a pity

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that both the two methods cannot measure the stress in the filler metal for the limitation of gauge volume. At present the minimum gauge volume of X-Ray and neutron beam is about 1 ~ 2 mm, which is much larger than the thickness of brazing filler metal [18]. Some researchers adopted the neutron diffraction to measure the brazed residual stress [19], however, the measured position located in the base metal rather than the brazing filler metal. Nano-indentation can measure the stress in the micro-region, but it requires a good smooth surface, and the cutting and grinding process will relax the residual stress in the brazed joint [20]. Hamilton et al. [21] pointed out that the validation of brazed residual stress is still further required. Therefore, it is very difficult to determine the brazed residual stress in the brazing filler metal by experimental method up to now.

With the development of computer technology, finite element method (FEM) is widely used to predict the residual stress in the brazed joint [22–24], and the residual stress in any region of the brazed joint can be obtained directly by the FEM. Zhang et al. [25] studied the residual stress in a brazed joint between the alumina and 304 stainless steel by FEM. The results demonstrated that Ni and Ni-Cr filler metals are compliant layers, and they are suitable to relieve the residual stress. Riccardo et al. [26] investigated the brazed residual stress in hybrid package for integrated substrate packaging applications, it is found that the residual stress in the substrate decreases with the thickness of barrier layer increases. Hamilton et al. [27] found that the thermal autofrettage can decrease the residual stress in brazed joint. Barrena et al. [28] studied the residual stress in the brazed joint between 90MnCrV8 steel and cemented carbide by FEM. The results illustrated that the residual stresses are very large and they can significantly decrease the joint strength. The maximum peak stress is located in the brazing filler metal-cemented carbide interface. Increase the brazing time can decrease the residual stress and thus improve the shear strength of the brazed joint. However, an excessive brazing time can generate intermetallic compound in the brazed joint, and in turn, decrease the strength of the brazed joint. He et al. [29] examined the residual stresses in Si_3N_4—CGM filler alloy-42CrMo joints by FEM. The effects of gradient material compositions, layer numbers and thicknesses on residual stresses have been discussed. It depicted that the CTE mismatch between the joined materials and the ability of plastic deformation in the brazing filler metal were the two factors that determine the residual stresses level in brazing joint. Jiang et al. [24,30] studied the effect of structure dimensions on residual stress in the compact plate-fin heat exchanger by FEM, which provides a guidance to improve the joint performance. For the hollow-tube stacking, V. Marcadon et al. [1] analyzed the mechanical behaviour by experimental characterization and modelling. It is found that the heterogeneity of the brazed joints generates stress concentration in the fillet. However, the distribution of brazed residual stress and how to decrease the residual stress are still need to be investigated. In this paper, the residual stress in a brazed hollow-tube stacking was investigated by finite element and experimental method, and the effects of tube diameter and cooling rate on the residual stress magnitude and distribution were fully discussed. Based on the calculated results, it is proposed to generate the compressive residual stress in the brazed joint by the self-expansion of tube to improve the strength of the whole joint.

2. Finite element modeling

2.1. Fabrication introduction of the hollow-tube stacking

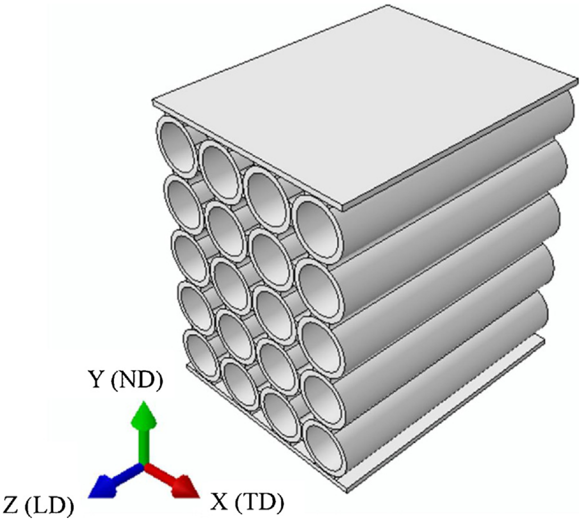

Fig. 1. Schematic of a hollow-tube stacking.

Fig. 1 shows a hollow-tube stacking consists of two sheets and a tube-stacking core. Tubes were stacked in a graphite die lined with sheets which positioned at the top and bottom. The brazing filler metal of BNi-2 was pre-positioned between the tubes and face plates. Then the assembly was clamped tightly to prevent the free movement of the substrate materials and brazing filler metal. The stacking was formed by high temperature brazing at a vacuum furnace, the assembly was firstly heated to 800 °C within 50 min and the temperature was held for about 30 min. Then it was heated to the brazing temperature of 1100 °C within 30 min and the temperature was lasted for about 25 min. At last, the assembly was cooled to the ambient temperature in the furnace. The melting temperature of filler metal BNi-2 is about 1020 °C. At the brazing temperature of 1100 °C, the brazing filler metal is liquid while the tube and plate are still solid. The filler metal flows into the gap between the two plates by wetting and capillary action. After cooling to the environmental temperature the assembly are joined together to form the stacking. The materials of the tube and plates are 316L stainless steel.

Due to the constraint and difference of mechanical properties between the tube and BNi-2, large residual stresses will be generated in the joint. In this paper, we developed a sequential coupling finite element method to study the brazing temperature and residual stress. The brazing temperature field was firstly simulated by a thermal analysis, and then the residual stresses were calculated by a thermal-elastic-plastic constitutive model.

2.2. Finite element model and meshing

As shown in Fig. 1, the outer diameter and thickness of tubes are 2 mm and 0.2 mm, respectively. The joint width is around 0.7 mm. The tube length is 10 mm. The plate length, width and thickness are 10 mm, 8 mm and 0.2 mm, respectively. The stacking is four tubes wide and five tubes high. Finite element software ABAQUS was used to calculate the temperature distribution and residual stress.

Fig. 2 shows the finite element meshing of the hollow-tube stacking. Dissimilar materials are assumed to be perfectly bonded at interfaces. The number of element and node are 201330 and 246977, respectively. The element type of temperature calculation is DC3D8, and stress analysis type is C3D8. In order to improve the calculation accuracy and save calculation time, the meshing around the brazed joints is refined and the other parts away from the joint are relatively coarse.