

Stress and Damage Analysis of the Innovative Brazing Seams between Al₂O₃ Ceramic and Nb Metal

F. Shi^{*1, 2}, B. Xu^{1, 2}, X. Wang³

¹Jiangsu Key Laboratory of Advanced Manufacturing Technology, Huaiyin Institute of Technology, Huaian, 223003, China

²Faculty of Mechanical and Material Engineering, Huaiyin Institute of Technology, Huaian, 223003, China

³Institute of Electronic Engineering, China Academy of Engineering Physics, Mianyang, 621999, China

received February 19, 2024; received in revised form August 11, 2024; accepted August 12, 2024

Abstract

This study employs numerical analysis to investigate the influence of seam structure on the residual stress and damage state in Al₂O₃ ceramic/Nb metal brazed structures. A block of Al₂O₃ ceramic and a Nb metal plate are connected with Ag-Cu-Ti filler under high temperature. Alongside the normal seam structure, three novel seam structures are proposed, including the groove-type seam structure, the hole-type seam structure, and the surrounding-cut seam structure. The residual stresses of all four Al₂O₃/Nb brazed structures are simulated with the finite element method (FEM). The numerical model is verified based on comparison with literature and the residual stress of the normal seam structure is checked against the experimental result. The findings demonstrate that the surrounding-cut seam structure is the most reliable since the surrounding groove can significantly reduce the harmful residual tensile stress by 29.5 % compared to the normal seam structure. Additionally, damage prediction conducted using ANSYS UPFs (User Programmable Features) confirms the reliability of the surrounding-cut seam structure. Besides, as an alternative, proper removal of the filler material from the seam edge can also reduce the harmful residual stress during the brazing process.

Keywords: Ceramic-metal joints, brazing, residual stress, finite element method, ceramic damage

I. Introduction

Ceramic materials play a pivotal role in applications where performance and reliability are paramount, such as in the aerospace and automotive industries^{1,2}. As a common engineering ceramic material, Al₂O₃ is widely used in a wide range of mechanical manufacturing and military equipment due to its excellent high-temperature properties and corrosion resistance^{3–6}. However, owing to their inherent brittleness, machining ceramic materials into complex shapes is challenging. In contrast, metal materials exhibit greater plasticity and ductility, allowing easier shaping in line with production requirements. Nevertheless, the high-temperature performance of metal materials is far inferior to that of ceramic materials. Fortunately, the combination of ceramic and metal in a joint structure enables effective complementarity. In actual engineering applications, ceramic and metal are usually connected by means of brazing^{7–9}. However, the difference in the coefficient of thermal expansion (CTE) between metals and ceramics leads to the generation of inevitable residual stress in the structure during the brazing cooling process^{10,11}. Residual stress is detrimental to the structure as it accelerates the failure of brittle materials.

Researchers have developed various methods to mitigate excessive residual stress in the brazing process and enhance the strength of the brazed structure. Zhang *et al.*¹² studied the effect of brazing temperature on the microstructure and mechanical properties of graphite/copper seams, and found that the maximal shear strength of the seam reached its highest value at a certain temperature. Similarly, Elrefaey *et al.*¹³ investigated the influences of brazing temperature and holding time on microstructures as well as on mechanical properties, highlighting temperature and time as crucial factors in controlling the microstructure and mechanical properties of brazed joints. Hernandez *et al.*¹⁴ designed an innovative structure for brazing titanium alloy with carbon-fiber-reinforced silicon carbide; their experimental results showed the strength of the brazed structure is effectively increased by adding perforations to the structure. Additionally, Zhang *et al.*¹⁵ investigated four different forms of seams for brazing oxygen-permeable membranes and metal supports, and found that the outer sleeve structure is the most reasonable based on a comparison of the residual stress. Wang *et al.*¹⁶ designed a three-layer filler consisting of Ag-Cu-Ti+TiNp/Cu/Ag-Cu to braze Si₃N₄ ceramic and Invar alloy, discovering that adding a copper foil intermediate layer to the filler can substantially reduce the residual stress in the brazed structure. Wang *et al.*¹⁷ investigated

* Corresponding author: shifang@hyit.edu.cn

the effect of rare earth elements on the microstructure and properties of 6061 aluminum alloy vacuum-brazing joints based on experiments, and found that structures containing rare earth elements exhibited higher strength. Jiang *et al.*¹⁸ studied residual stress and creep in a stainless-steel plate-fin structure, and their results demonstrated that the thickness of filler metal played an important role in seam strength. In other words, properly adjusting the thickness of filler metal can reduce the residual stress to a certain extent. At present, despite the comprehensive research on optimizing brazing residual stress, there has been only limited systematic exploration of seam design from a structural perspective. The selection of reliable seam structures can effectively relieve the harmful residual stress in the brazing process¹⁵, which is of great importance for further strengthening the brazed structure.

This study seeks an optimized seam structure by means of stress simulation and damage prediction. Based on the common $\text{Al}_2\text{O}_3/\text{Nb}$ brazing model, three novel models with different seam geometric structures are designed. To examine the reliability of several models, the residual stress and damage of each model under the same brazing conditions are compared and analyzed using the finite element method. Based on analysis of different forms of brazing seam, some references for the optimization of similar brazed structures are provided. The finite element simulation is chosen as the primary method for this study after verification of the proposed numerical model, and the residual stress of the normal seam structure is checked against experimental results.

The structure and content of this paper are organized as follows. Firstly, the FEM-based brazing models of several geometric structures are established, and then verified with experimental results. Based on the comparative analysis of residual stresses of different structures, a more reliable brazed structure is found. Secondly, size adjustments to the selected model are made to further reduce its residual stress. Finally, by using the secondary development of ANSYS, the elastic damage simulation of brittle material is realized to show the damage state in ceramics.

II. Numerical Model

(1) Model description

Al_2O_3 ceramic and Nb metal are used as basic materials^{19–21}. An Al_2O_3 ceramic block with a purity of 95 % is cut into a $6 \times 6 \times 6 \text{ mm}^3$ small block. Similarly, a Nb metal plate with a purity of 99.9 % is cut into an $18 \times 12 \times 2 \text{ mm}^3$ plate. A 70Ag–28Cu–2Ti foil with a thickness of $200 \mu\text{m}$ is used as the interlayer to connect the ceramic block and the metal plate by means of vacuum brazing. It should be noted that the thickness of the interlayer has a non-negligible influence on the residual stress. However, in this study, our focus is on the residual stress of four $\text{Al}_2\text{O}_3/\text{Nb}$ brazing structures with distinct geometric configurations of the seam. Therefore, a constant thickness of $200 \mu\text{m}$ for the interlayer is maintained throughout this paper. The normal model is illustrated in Fig. 1.

Three innovative $\text{Al}_2\text{O}_3/\text{Nb}$ models with different seam structures are designed to seek a more reliable brazed model. Based on the different forms of brazing seams, they

are named the groove-type seam structure, hole-type seam structure, and surrounding-cut seam structure in this paper. In the three models, the geometry of the Nb plates is adjusted separately because of the high plasticity of the metal material. Dissection diagrams of four models and three-view drawings of different Nb plates are shown in Fig. 2. The specific Nb plates can be inferred based on different three-view drawings. The groove-type seam structure is illustrated in Fig. 2 (b), and both the width and depth of the groove measure $400 \mu\text{m}$. Specifically, the groove of the Nb plate can be machined with the milling cutter. Fig. 2 (c) shows the geometry of the hole-type seam structure. The size of each square through-hole is $400 \times 400 \mu\text{m}^2$, and the spacing of each hole is 1 mm . In addition, the number of the through-holes is 25, and the through-holes can be machined by means of laser drilling. As seen in Fig. 2 (d), a part of Nb metal is cut around the brazing seam in the surrounding-cut seam structure. Both the width and depth of the surrounding groove measure $400 \mu\text{m}$. The outer edge length of the groove in the surrounding-cut seam structure is 6 mm , which is the same as the length of the bottom edge of the ceramic block. It should be noted that the filler above the groove is removed. Reliable clamps and auxiliary tools can be used for brazing the above parts to keep the structure stable²². If necessary, the parts can be inverted to prevent excessive filler metal from flowing into the grooves or holes during melting at a high temperature.

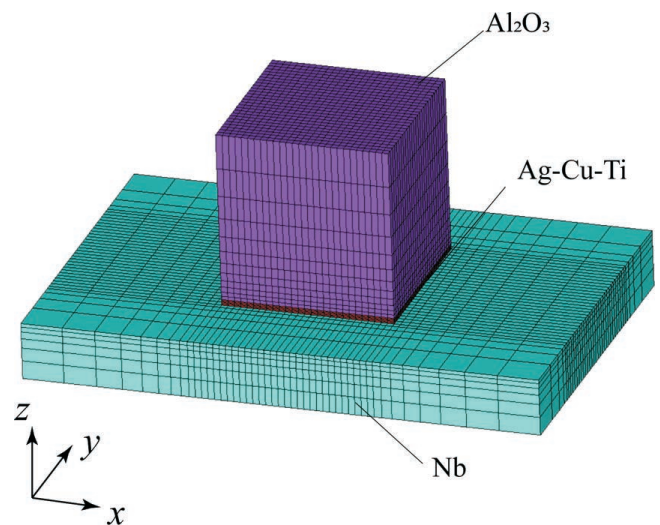


Fig. 1: Three-dimensional model of the normal $\text{Al}_2\text{O}_3/\text{Nb}$ model and its finite element mesh. The purple part represents Al_2O_3 ceramic, the red part represents Ag–Cu–Ti filler, and the blue part represents Nb metal.

(2) Material parameters

The physical parameters of materials are crucial for the simulation, especially the CTE and elastic modulus at different temperatures. In this paper, the physical parameters of the material are determined by consulting relevant literature^{23–26}. The parameters of materials at different temperatures for some materials with incomplete data are obtained by interpolation concerning the given typical temperature values²⁷. The physical parameters of materials adopted in the simulation are listed in Table 1.

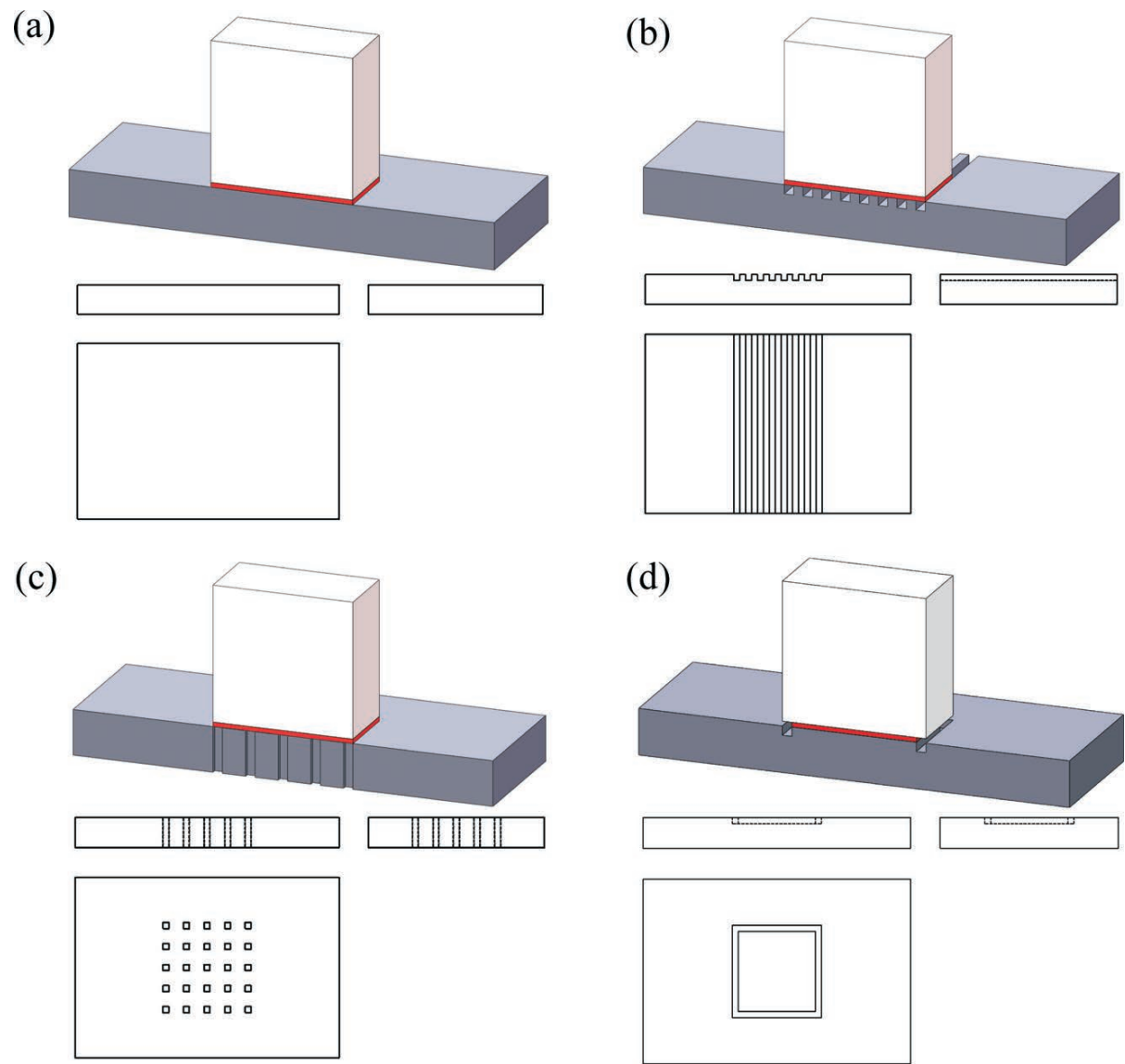


Fig. 2: Schematic diagrams of different Nb metal three-dimensional models: (a) normal seam structure, (b) groove-type seam structure, (c) hole-type seam structure, and (d) surrounding-cut seam structure.

Table 1: Physical properties of materials used in the FEM simulation.

Material	Temperature (°C)	Elastic modulus (GPa)	Poisson's ratio	CTE (10 ⁻⁶ K ⁻¹)	Yield stress (MPa)
Al ₂ O ₃	25	304	0.2	6.8	/
	300	295	0.2	7.0	/
	500	284	0.2	7.4	/
	800	269	0.2	7.8	/
Ag-Cu-Ti	25	94	0.35	16	200
	300	85	0.35	18.4	120
	500	60	0.36	20.7	60
	800	20	0.37	22	20
Nb	25	120	0.33	7.3	70
	300	110	0.33	9.2	68
	500	90	0.34	10.7	66
	800	75	0.34	12.2	65

(3) Simulation procedure

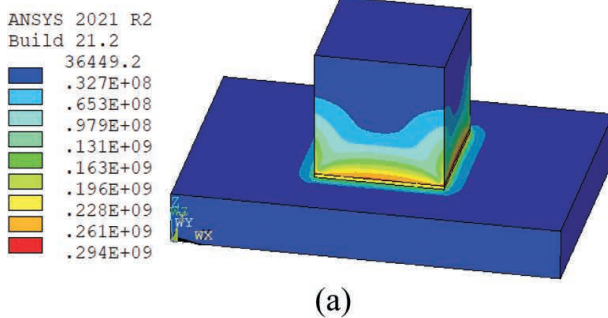
Generally, it is difficult for ceramic materials to form a firm combination with filler, so the brazing surface of ceramics is usually metallized in advance²⁸. The simulation step of surface metallization is omitted in this paper because the thickness of the metallization zone is extremely thin, and it is hard to achieve accurate simulation. Respectively, four three-dimensional models are established with the use of APDL (ANSYS Parametric Design Language). With the use of APDL, the numerical model can be established in a parametric and efficient way. To ensure the accuracy of the simulation, each model is divided into an appropriate mesh. As the meshes become denser, the simulation workload and time increase considerably. Therefore, it is essential to strike a balance between accuracy and computational efficiency. As shown in Fig. 1, the non-uniform mesh method from dense to sparse is adopted in this paper to improve simulation efficiency. The meshes at the brazing seam are relatively dense, and the meshes away from the brazing seam become gradually sparser. In general, the residual stress at the brazing position changes significantly, therefore, the Ag-Cu-Ti filler is divided into five layers of mesh in the Z-direction. It is worth noting that for a more accurate experimental comparison, the meshes of the four models are set to roughly the same. In addition, the X-direction, Y-direction, and Z-direction of the 3D coordinate system represent the length direction, width direction, and height direction of the model respectively, and the Z-direction degrees of freedom of the four corners at the bottom of the model are constrained. The thermal analysis method in ANSYS is used to simulate the residual stress generated in the cooling stage of the brazing process. The melting point of the Ag-Cu-Ti filler metals is

780 °C²⁹, therefore, the temperature is increased to 800 °C to melt the filler. The structure is in a stress-free state at this temperature. After a short time during which the level of heat is maintained, the model temperature is cooled to 200 °C at the rate of 5 K/min. Finally, the model temperature is reduced to room temperature at the rate of 2 K/min.

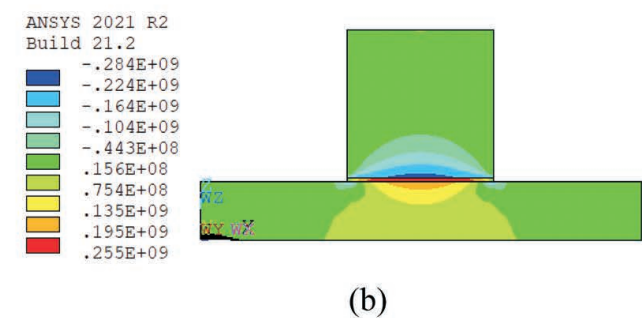
(4) Model verification

The model established in this paper is verified based on comparison with the results reported by Wang *et al.*²⁴ in which Al₂O₃ ceramic with the dimension of 5 x 5 x 5 mm³ and Nb metal with normal seam structure was brazed with an Ag-Cu-Ti inter-layer. In their study, the brazing process was simulated and the maximum residual Mises equivalent stress is 296.2 MPa, which agrees well with experimental result²⁴. In this study, the finite element model incorporated in ANSYS, which can be accessed from GitHub (https://github.com/PhiPsi-Software/Brazing_Simulation), leads to the residual stress distribution as shown in Fig. 3. It can be seen from Fig. 3 (a) that the maximum residual Mises equivalent stress is 294 MPa, with a difference of only 0.7 % compared to the literature²⁴, indicating the reliability of the established numerical model. From the stress contour in the X-direction (Fig. 3 (b)), it can be observed that Al₂O₃ ceramic is subject to compressive stress of 284 MPa, while the filler experiences tensile stress of 255 MPa, and this conclusion is consistent with the literature^{16,24,26,29}. The final temperature distribution of this verification case is shown in Fig. 3 (c), where it can be seen that the model has reached room temperature with a maximum difference of less than 0.1 degrees Celsius. The maximum principal stress occurs in the filler region, as shown in Fig. 3 (d).

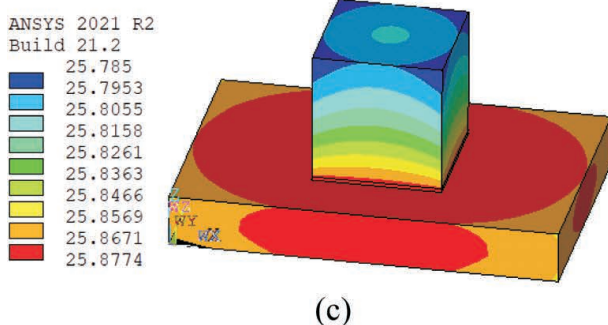
Unit: MPa



Unit: MPa



Unit: °C



Unit: MPa

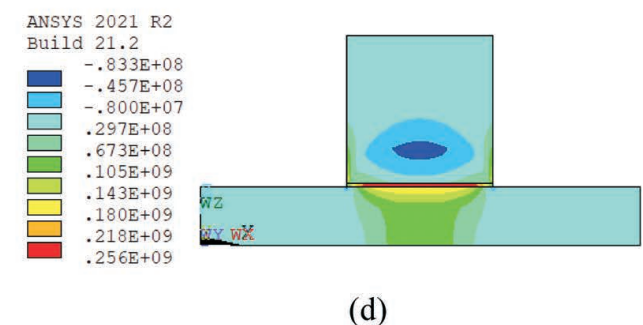


Fig. 3: Contours of the verification case: (a) Mises equivalent stress, (b) stress in X-direction, (c) the final temperature, and (d) maximum principal stress.

III. Results and Analysis

(1) Finite element simulation results

Due to the inconsistent CTE parameters between ceramic and metal, residual stress will inevitably occur in the structure after brazing³⁰. As a general rule, the highest residual stress typically occurs at the brazing seam. In this study, the Ag-Cu-Ti interlayer is removed for post-processing after simulation to better observe the magnitude and distribution of residual stress in the Al₂O₃ block. As illustrated in Fig. 4, The simulated results include the *X*-direction stress contour plot (Fig. 4 (a)), *Y*-direction stress contour plot (Fig. 4 (b)), *Z*-direction stress contour plot (Fig. 4 (c)), and shear stress contour plot (Fig. 4 (d)) of the normal Al₂O₃/Nb structure. Fig. 4 (a) and Fig. 4 (b) show similar magnitudes and distributions of stress in the *X*-direction and *Y*-direction due to the structural symmetry. The Al₂O₃ ceramic, with a much higher elastic modulus than the Nb metal, severely restricts the deformation of the Nb metal plate during high-temperature brazing, leading to significant residual stress at the bottom of the Al₂O₃ block. The compressive stress near the seam in the ceramic is particularly high, reaching a maximum value of 410 MPa. Fig 4 (c) illustrates the distribution of the *Z*-direction stress, showing high tensile stress at the sides of the ceramic with a maximum value of 139 MPa. This tensile stress arises from the higher coefficient of thermal expansion of the Nb plate compared to that of the ceramic, causing it to be restrained by the ceramic and to curl vertically during cold shrinking. As a result, the ceramic edge experiences substantial vertical tension. Considering

the brittleness of ceramic, which cannot withstand excessive tensile stress, it is crucial to attenuate the *Z*-direction stress in subsequent research. Fig. 4 (d) presents the shear stress (τ_{xy}) contour plot of the normal structure, showing a regular distribution of shear stress on the Nb plate with a maximum value of only 55 MPa. The residual stress in the Al₂O₃ ceramic of the normal Al₂O₃/Nb structure was measured with XRD (EMPYREAN, Netherlands). As shown in Fig. 5, the path indicated by a black dotted line for the residual stress test is taken in the Al₂O₃ ceramic, 0.5 mm away from the filler. The measured residual compressive stress is 199.6 MPa, slightly larger by 9 % than the simulated value of 183.1 MPa. The observed phenomenon, where the experimental results are slightly larger than the numerically simulated values, is consistent with other findings reported in the literature^{23,31}.

Von Mises stress is widely used in the analysis of brazing residual stress³², it can be used as a criterion for measuring structural reliability. The von Mises stress contour plots of several structures simulated with the finite element method are presented in Fig. 6. It is obvious that high residual stress always appears in the Al₂O₃ ceramic block near the brazing seam. The maximum von Mises stress values of several structures are compared with each other, and the maximum stress of the groove-type seam structure is the highest. As shown in Fig. 6 (b), the maximum stress is 441 MPa, because the residual stress above each groove is significantly increased. Besides, based on the comparison of stress states in the normal seam structure (Fig. 6 (a)), the hole-type seam structure (Fig. 6 (c)), and the surrounding-cut seam structure (Fig. 6 (d)), the maximum residual

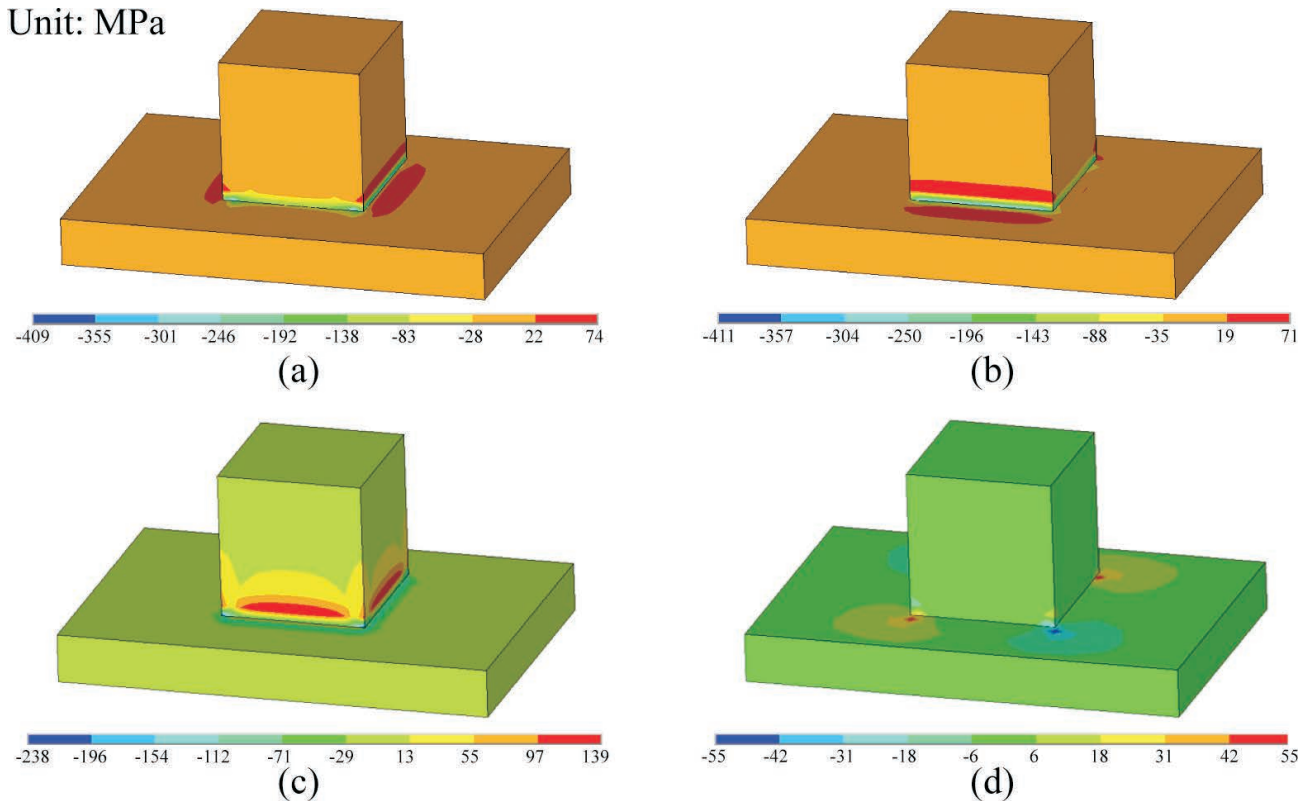


Fig. 4: The residual stress contour plots of the normal Al₂O₃/Nb structure: (a) *X*-direction stress contour plot, (b) *Y*-direction stress contour plot, (c) *Z*-direction stress contour plot, and (d) shear stress (τ_{xy}) contour plot.

stress values of the three structures are extremely close, being 388 MPa, 389 MPa, and 386 MPa respectively. However, their stress gradients change inconsistently. The stress contour of the normal seam structure changes rapidly, especially at the brazing seam. In comparison, the stress contour of the hole-type seam structure and the surrounding-cut seam structure changes slowly because of their distinctive geometries.

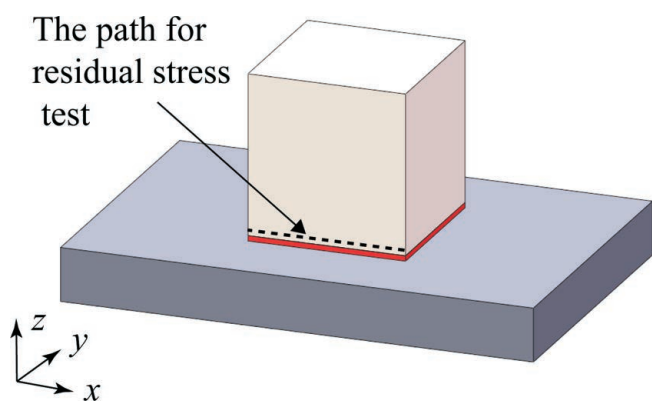


Fig. 5: The path for the residual stress measurement experiment.

To investigate the residual stress in the different structures more closely, several schemes are designed to research the stress state of the structure, as shown in Fig. 7. The first scheme is designed to study the stress distributions of section A and section B, section A is the XZ plane

in the middle of the model and section B is the XY plane between the Al_2O_3 ceramic block and Ag-Cu-Ti filler. Besides, stress contour plots of two sections are obtained respectively. The second scheme is used to extract the stress data on the C-C path and D-D path, we set the middle of the bottom of the ceramic block in the X -direction as the C-C path, and the D-D path is the line along the Z -direction in the middle of the side of the ceramic block. Moreover, the stress states in the different brazed structures are analyzed based on plotting of the stress curves.

Fig. 8 illustrates the von Mises stress distribution in section A of different brazed structures. Compared with external von Mises stress, internal stress is also roughly the same. High residual stress occurs on both sides of the ceramic block bottom. However, there are certain differences in the distributions of internal and external stress. When compared with the normal seam structure (Fig. 8 (a)) and the surrounding-cut seam structure (Fig. 8 (d)), the stress distribution of the normal seam structure is similar to that of the surrounding-cut structure, but the area of higher stress in the structure of the surrounding-cut seam is much smaller. As shown in Fig. 8 (b), due to the multi-groove geometry of the Nb plate, the stress distribution on the Nb plate is different from that of other structures. In addition, the stress on both sides of the ceramic block bottom becomes more concentrated. In the hole-type seam structure (Fig. 8 (c)), the residual stress can be relieved to a certain extent by the through-holes.

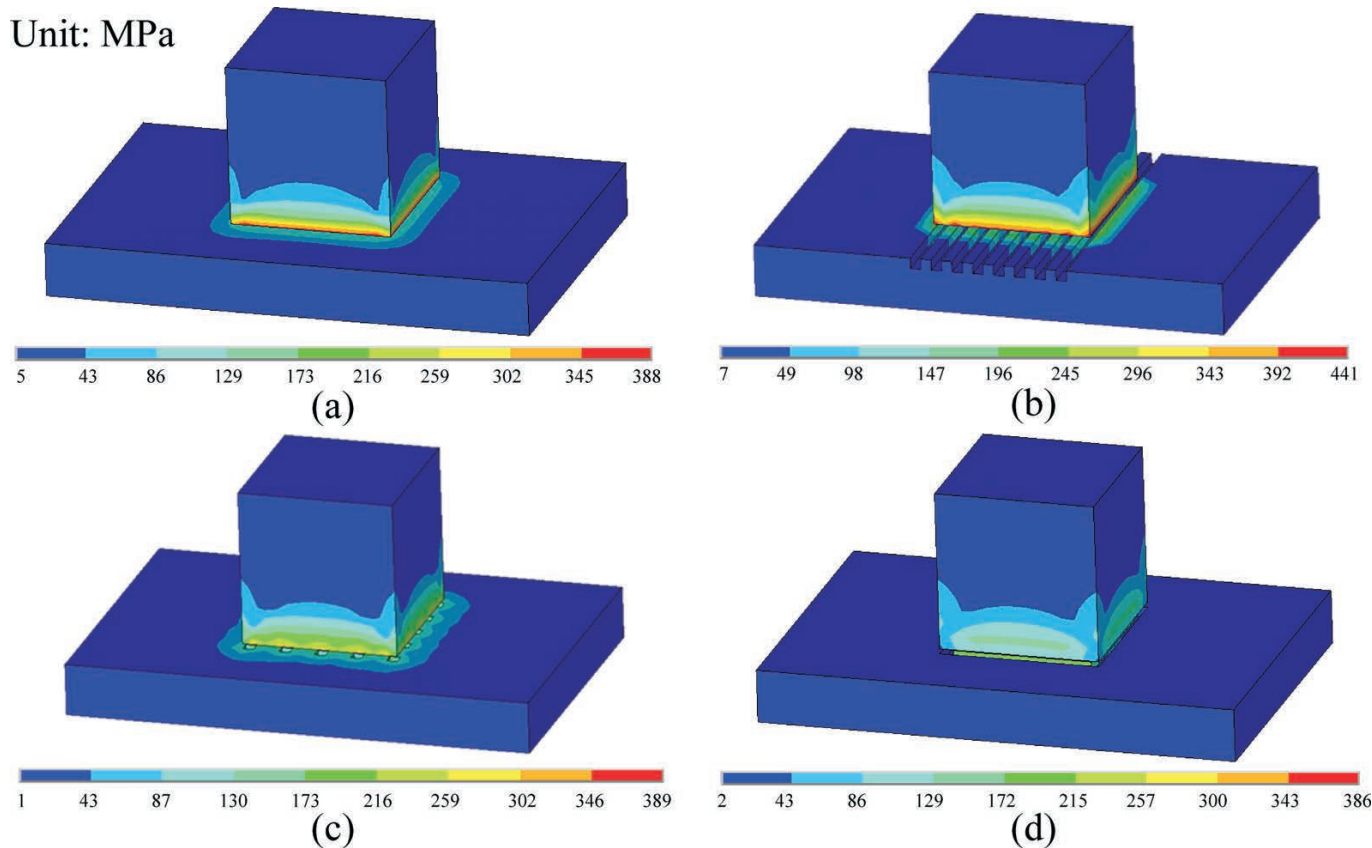


Fig. 6: Von Mises stress contour plots of four different $\text{Al}_2\text{O}_3/\text{Nb}$ structures: (a) normal seam structure, (b) groove-type seam structure, (c) hole-type seam structure, (d) surrounding-cut seam structure.

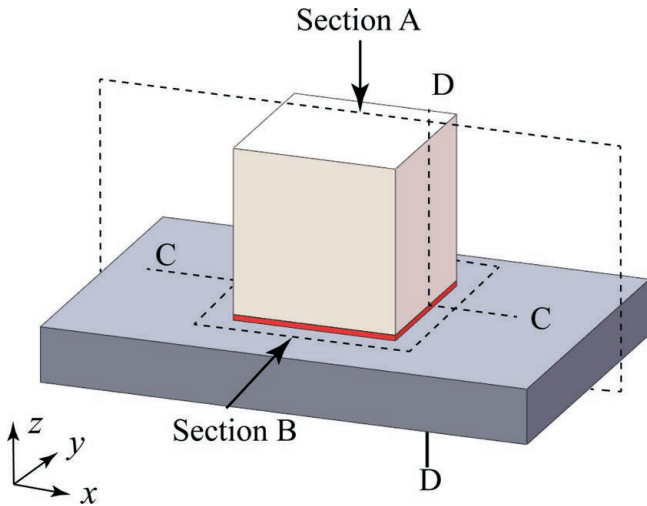


Fig. 7: Schematic diagram of section and path used in the study: (a) Section A: the XZ plane in the middle of the model, (b) Section B: the XY plane under the Al_2O_3 ceramic block, (c) C-C path: the line along the X-direction in the middle of the bottom surface of Al_2O_3 ceramic block, (d) D-D path: the line along the Z-direction in the middle of the ceramic side.

Von Mises stress distributions in section B of four different brazed structures are illustrated in Fig. 9. Obviously, the residual stress at the center of the ceramic bottom is less than that around the ceramic bottom. Based on the result of Fig. 9 (a) and Fig. 9 (c), it is found that the distribution of the maximum stress is roughly the same, but there are obvious differences in the stress contour.

Compared with the normal seam structure, the stress contour of the hole-type seam structure changes more slowly. From Fig. 9 (b) we can see the stress under the ceramic block in the groove-type seam structure. Due to the structure of the Y-direction groove, the von Mises stress in the Y-direction becomes more concentrated. As presented in Fig. 9 (d), the maximum stress in the surrounding-cut seam structure also appears in the four corners of the ceramic block bottom, but the area with high stress is also significantly reduced. It can be concluded that the groove around the seam can reduce the residual stress of the ceramic block and make the stress contour change more slowly.

The von Mises stresses of the C-C path with four different brazed structures are extracted, and the curves of stress variation along the C-C path are shown in Fig. 10 (a). The von Mises stress at both ends of the path in each structure is relatively high, meanwhile, the residual stress in the middle of the ceramic is stable at a low level. In the groove-type seam structure and the hole-type seam structure, the stress at the position about $600\ \mu\text{m}$ inward at both ends reaches the maximum. Compared with the normal seam structure, the von Mises stress distribution of the groove-type seam structure in the C-C path is similar, but the residual stress clearly at both ends of the groove-type seam structure as a whole. Moreover, the stress of the surrounding-cut seam structure is the lowest, its maximum stress value being $297\ \text{MPa}$. According to the result of Fig. 4 (c), the maximum tensile stress in the Z-direction appears on the side of the ceramic block. As a result, it is crucial to explore the Z-direction stress on the D-D path. The Z-direction stress

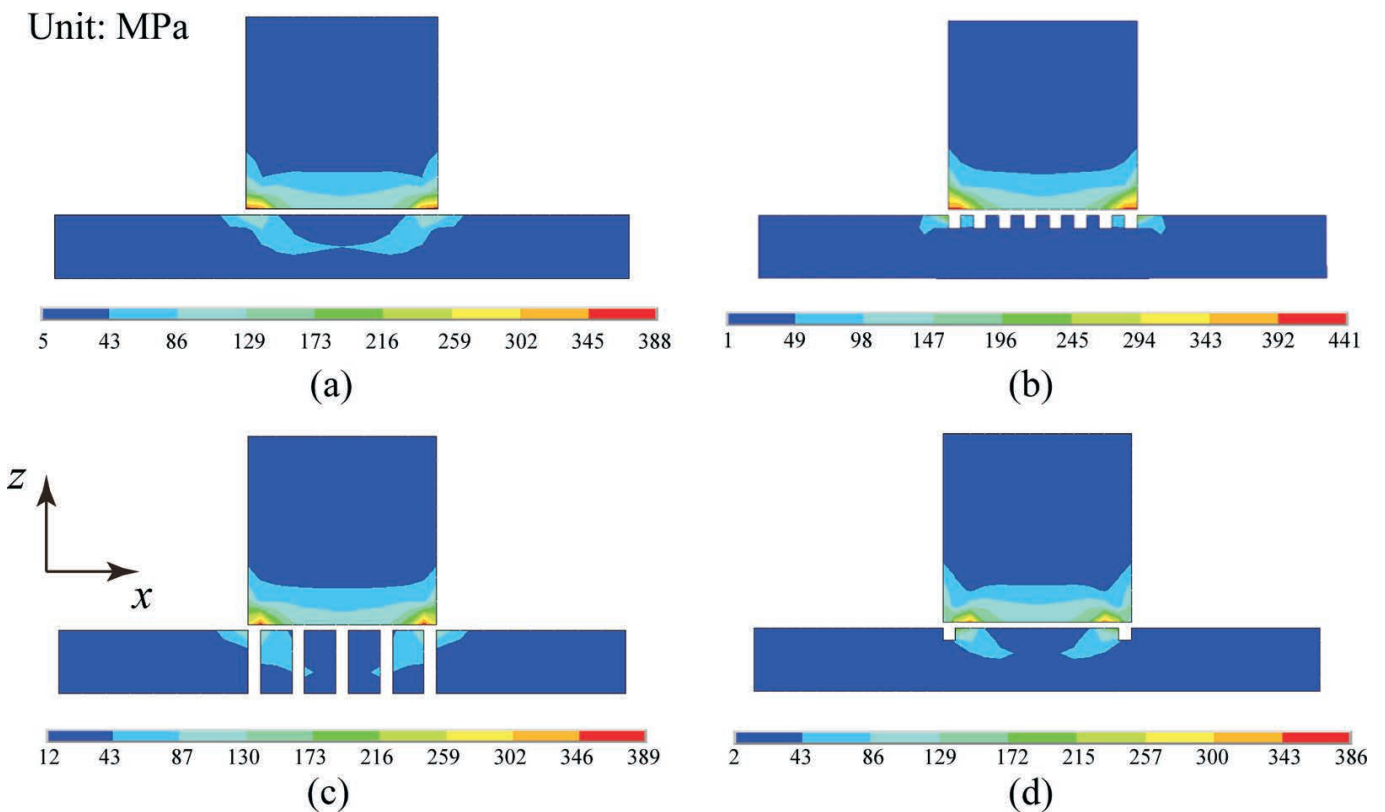


Fig. 8: Von Mises stress contour plots of section A of different structures: (a) normal seam structure, (b) groove-type seam structure, (c) hole-type seam structure, and (d) surrounding-cut seam structure.

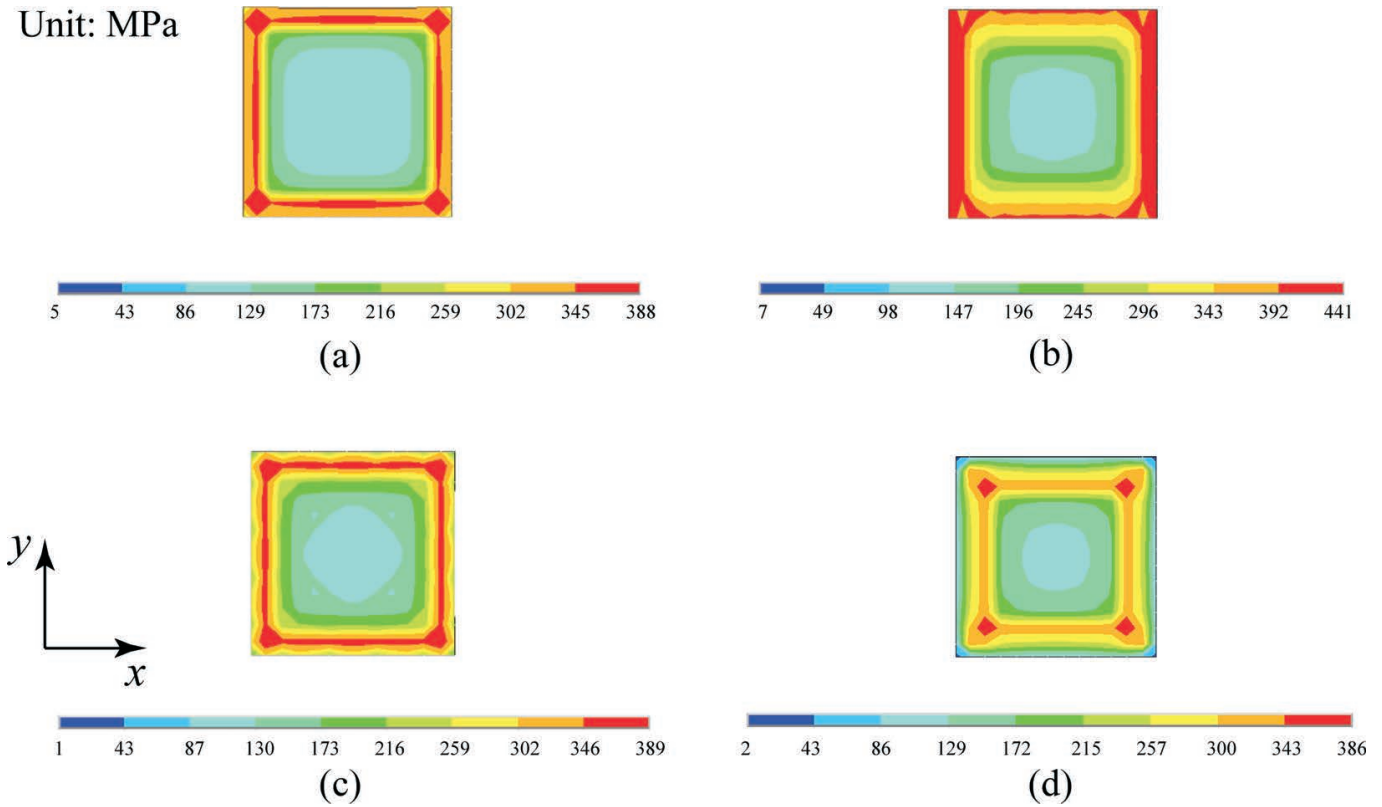


Fig. 9: Von Mises stress contour plots of section B of different structures: (a) normal seam structure, (b) groove-type seam structure, (c) hole-type seam structure, and (d) surrounding-cut seam structure.

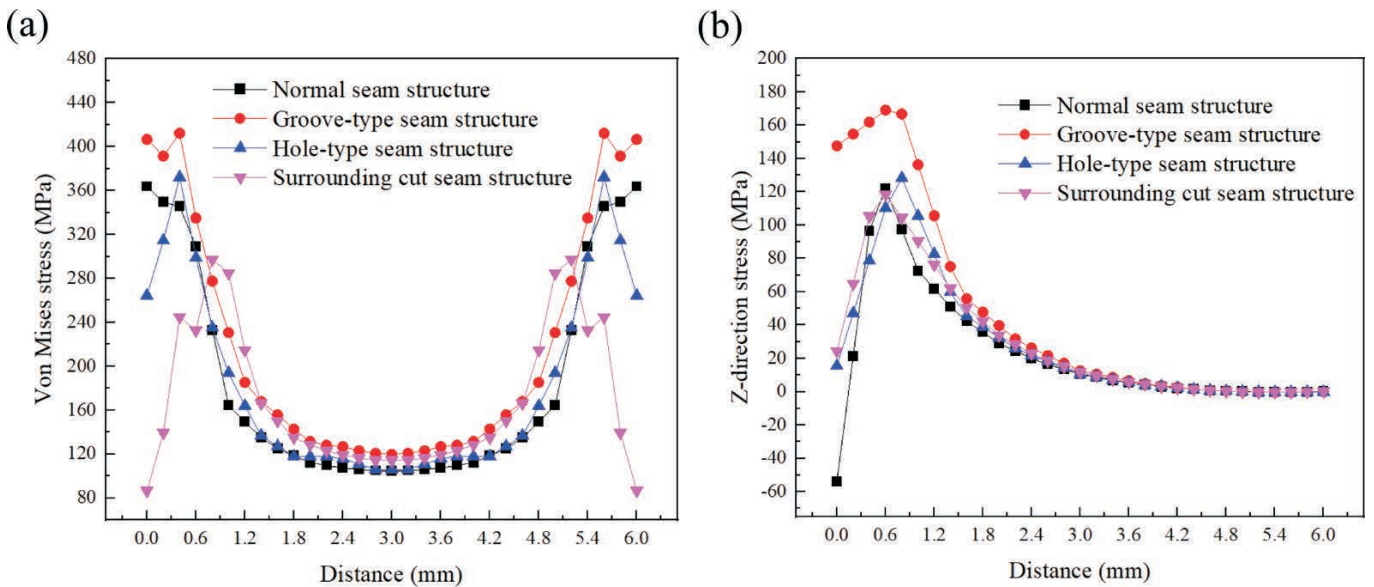


Fig. 10: The curves of stress variation along two paths: (a) von Mises stress curve on the C-C path, (b) Z-direction stress curve on the D-D path.

curves on the D-D path are illustrated in Fig. 10 (b). The maximum Z-direction stress appears at the position of about 800 μm from the ceramic side to the brazing seam, and the Z-direction stress gets smaller and smaller the further away from the brazing seam. The reason for this stress generation is that the ceramic block restricts the deformation of the Nb plate in the brazing process, which causes

the Nb plate to apply more loads on the bottom edge of the Al_2O_3 ceramic in the Z-direction. The Z-direction stress of the surrounding-cut seam structure is slightly smaller than that of the normal seam structure at the peak value, and its stress changes more slowly because the existence of the surrounding groove can effectively reduce the loads in the bottom edges of the ceramic block. Moreover, it is

worth noting that the maximum Z-direction stress on the D-D path is slightly lower than that on Al₂O₃ ceramic because the width of the Nb plate is less than the length. Based on measurements, the maximum Z-direction stress occurs on the side of the ceramic in the XZ-directions.

(2) Influence of structure size on stress

The stress contour in the hole-type seam structure changes slowly due to the existence of holes. To further investigate the impact of the hole-type seam structure on residual stress, the sizes of the through-hole in the hole-type seam structure are adjusted. The size of the square through-hole is set to 300 μm , 350 μm , 450 μm , and 500 μm , respectively, and the finite element simulations are performed for each model. The maximum von Mises stress and the maximum Z-direction stress in the Al₂O₃ ceramic block are extracted and compared, as shown in Fig. 11 (a). The von Mises stress decreases as the through-hole size increases, indicating that the through-hole can disperse some of the residual stress. Moreover, the harmful Z-direction tensile stress increases with larger through-hole sizes, causing greater harm to the ceramic. In practice, the von Mises stress of the brazed structure cannot be reduced by arbitrarily increasing the size of the

through-hole. Theoretically, both the von Mises stress and Z-direction stress are at appropriate levels when the size of the through-hole is around 400 μm .

Comparison of residual stresses in four different structures reveals that the surrounding-cut seam structure is the most reliable. To obtain an optimal size of the surrounding groove, the width and depth of the surrounding groove of the model are adjusted, respectively. Firstly, while the depth of the surrounding groove is kept unchanged, the groove with the original width of 400 μm is adjusted to 300 μm , 350 μm , 450 μm , and 500 μm , respectively. Each model is established and simulated by means of the finite element method, with recorded results focusing on the maximum von Mises stress and the maximum Z-direction stress in the different structures. Secondly, the groove with the original depth of 400 μm is adjusted to 300 μm , 350 μm , 450 μm , and 500 μm , respectively, while the width of the surrounding groove remains unchanged. Curves showing the relation of the width and depth of the surrounding groove to stress are presented in Figs. 11 (b) and (c). According to Fig. 11 (b), it is obvious that the width of the surrounding groove has a significant effect on the residual stress. As the groove becomes wider, both von Mises stress

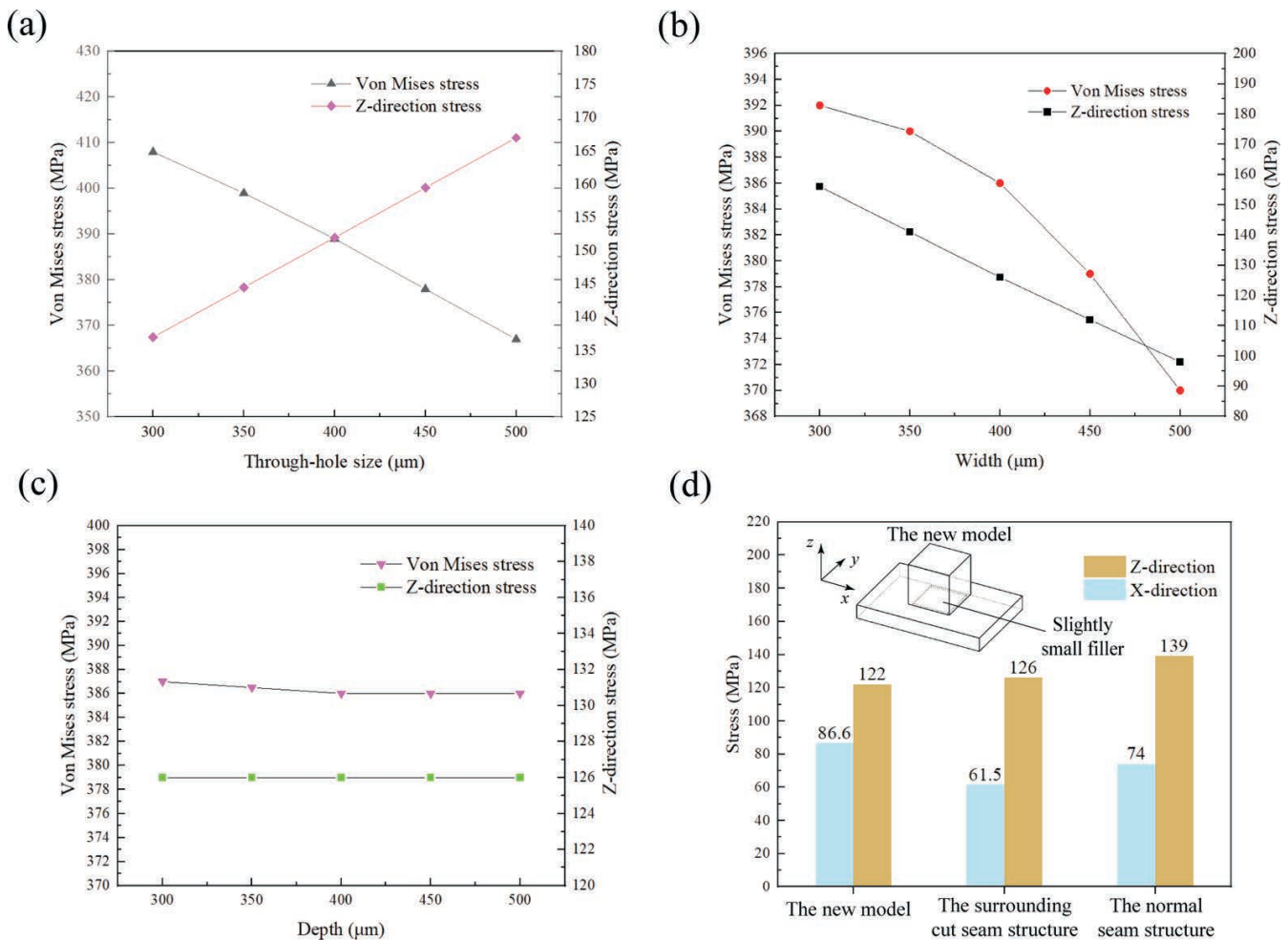


Fig. 11: Comparison diagram of the effect of specific dimensions on stress: (a) The maximum stresses in ceramic blocks with different sizes of holes, (b) The maximum stress in ceramic blocks with different widths of surrounding grooves, (c) The maximum stress in ceramic blocks with different depths of surrounding grooves, and (d) Comparison diagram of maximum X-direction stress and maximum Z-direction stress of three models: the new model, the surrounding-cut seam structure and the normal seam structure.

and Z-direction stress decrease gradually, part of the reason for this result is the reduction of the surface area of the Ag-Cu-Ti filler used for brazing. However, it should be noted that the processing size cannot be arbitrarily increased, and an excessively wide surrounding groove will inevitably reduce the strength and stability of the composite structure. The curves in Fig. 11 (c) indicated that the adjustment of the depth of the surrounding groove has little effect on the von Mises stress. The von Mises stress of the Al_2O_3 ceramic decreases slightly with the increase in depth. However, the von Mises stress on the ceramic will not change when the depth of the surrounding groove reaches a certain extent. Conversely, the Z-direction stress remains stable at 126 MPa regardless of the depth. Based on the simulation results, optimizing the surrounding groove with a width of 500 μm yields superior results, with a maximum von Mises stress of 370 MPa and a maximum Z-direction stress of only 98 MPa, as found in this study.

For an in-depth investigation of the effects of the surrounding groove, the depth of the surrounding groove in the surrounding-cut seam structure is adjusted to zero, resulting in a configuration similar to the normal seam structure where the area from the seam edge of the filler is reduced. As shown in Fig. 11 (d), the X-direction stress and Z-direction stress of the new brazed model are simulated. The simulation results are then compared with those of the surrounding-cut seam structure and normal seam structure. According to the simulations, the structure with filler reduction exhibits the lowest maximum Z-direction stress, measuring 122 MPa, which is close to the stress level of the surrounding-cut seam structure. However, the maximum X-direction stress is higher in the structure with filler reduction compared to the other two models. Specifically, its X-direction tensile stress is 41 % higher than that of the surrounding-cut seam structure. Overall, the structure with filler reduction is superior to the normal seam structure but inferior to the surrounding-cut structure. Proper reduction of the filler metal area can effectively mitigate harmful residual stress during the brazing process.

IV. Damage Model and Prediction

Various microcracks exist in ceramic materials, so ceramic materials can be easily damaged when subjected to high stresses^{33–35}. To study the damage in the Al_2O_3 ceramic block, a model that considers the damage is developed by using the ANSYS user subroutine usermat. In this paper, the scalar D in the range 0 to 1 is used to represent the damage. When D is 0, the structure is perfect without damage, whereas the structure is completely damaged when D reaches 1^{36, 37}.

(1) Damage principle

The tensile damage constitutive equation derived from the tensor expression is³⁸:

$$\sigma_{ij} = (1 - D)E_{ijkl}\epsilon_{kl} + \frac{D}{3}\delta_{ij}E_{ppkl}\epsilon_{kl} \quad (1)$$

where σ_{ij} is the real stress tensor and ϵ_{kl} is the real strain tensor, E_{ijkl} is the elastic tensor, δ_{ij} is the Kronecker delta, and D is the damage factor.

Strain is the main controlling factor of damage evolution in this study. In Eq. (2), ϵ is the actual strain. The threshold strain of ceramic damage evolution under a uniaxial state is set as ϵ_f . If the strain is below this threshold, there is no damage. The strain at the damage limit is ϵ_u . Then, the damage evolution equation can be written as^{38, 39}:

$$D = \begin{cases} 0, & 0 < \epsilon < \epsilon_f \\ \frac{\epsilon_u(\epsilon - \epsilon_f)}{\epsilon(\epsilon_u - \epsilon_f)}, & \epsilon_f < \epsilon < \epsilon_u \end{cases} \quad (2)$$

The parameters ϵ_f and ϵ_u are calculated based on uniaxial tests. The tensile strain parameter is determined in the uniaxial tensile test, and the compressive strain parameter is determined in the uniaxial compression test. In general, in the stress-strain diagram obtained from the uniaxial test of brittle materials, the intersection of the elastic linear part and the damaged curve part can be regarded as the damage threshold point. In this study, the damage parameters of ceramic are listed in Table 2^{40, 41}.

For a three-dimensional stress state, its equivalent strain⁴² is:

$$\epsilon = \sqrt{\epsilon_1^2 + \epsilon_2^2 + \epsilon_3^2} \quad (3)$$

where ϵ_1 , ϵ_2 , and ϵ_3 are the principal strains. The equivalent tensile strain can be obtained as:

$$\epsilon_t = \sqrt{\sum_i \epsilon_i^2} (\epsilon_i > 0) \quad (4)$$

Similarly, the equivalent compressive strain can be written as:

$$\epsilon_c = \sqrt{\sum_j \epsilon_j^2} (\epsilon_j < 0) \quad (5)$$

The total damage is defined as:

$$D = \alpha_t D_t + \alpha_c D_c \quad (6)$$

where D_t and D_c are the tensile and compressive damage factors calculated from Eq. (2) by using tensile and compressive strain parameters separately. In addition, α_t and α_c in Eq. (6) are obtained with the following equation:

$$\alpha_t = \left(\frac{\epsilon_t}{\epsilon}\right)^2, \alpha_c = \left(\frac{\epsilon_c}{\epsilon}\right)^2 \quad (7)$$

Table 2: Damage parameters.

	Damage threshold strain ϵ_f	Damage limit strain ϵ_u
Tensile	0.0003	0.0032
Compressive	0.0008	0.0023

(2) Damage prediction

This paper establishes a model in the ANSYS usermat user subroutine to obtain the value of the damage factor D . The Fortran file (*usermat.f*) can be expediently accessed from GitHub (https://github.com/PhiPsi-Software/Brazing_Simulation). The damage constitutive equation is coded into the ANSYS program. Meanwhile, the possible

damage in the Al_2O_3 ceramics of four different structures is simulated respectively, and the damage in the ceramics is preliminarily analyzed from the obtained theoretical results.

The contour plot of damage distribution in the normal seam structure is illustrated in Fig. 12 (a). The damage degree of the Al_2O_3 block is relatively high at the position of about 0.5 mm from the seam. Especially, the maximum damage factor D reaches 0.924 in the middle of the four surfaces in this area according to the damage prediction for ceramic, which means that cracks are more likely to occur in these areas. On the basis of a comparison with Fig. 3 (c), the damage contour is similar to the Z-direction stress contour in the brazed structure, it indicates that the damage is closely related to the higher Z-direction tensile residual stress. It can be seen from Table 2 that the tensile damage threshold of ceramic is lower than the compression damage threshold of ceramic, so the tensile strain has a greater impact on the damage of the ceramic. Besides, it can be seen from the different sides of the ceramic block that the damage distribution in the X-direction is close to the damage in the Y-direction, but there is a tiny difference in the magnitude of damage. The reason for the above results is that the length ratio of the Nb plate at the bottom of the ceramics is wider than the width ratio, which increases the strain on the XZ side of the ceramic block.

The damage prediction results of four different structures are shown in Fig. 12. Of these, the maximum damage factor D of ceramic in the groove-type seam structure is the highest, with a predictive value of 0.935. Conversely,

the maximum damage factor D of ceramics in the surrounding-cut seam structure is the lowest, with a predictive value of 0.866. Moreover, the maximum damage positions of the four different structures are roughly consistent. Fig. 12 (b) presents the ceramic damage prediction of the groove-type seam structure. As with the normal seam structure, the distribution of damage of ceramic in the groove-type seam structure is roughly the same. However, there are small differences in details. The Y-direction grooves reduce the damage of the ceramic in the X-direction to some extent, but it seems that the damage in Y-direction increases a little and the damage become more concentrated. The above results are consistent with the reason for the difference in stress distribution of the groove-type seam structure mentioned in this study. The damage contours plot of the hole-type seam structure is illustrated in Fig. 12 (c), the damage on the side of the ceramic is relieved to a certain extent under the influence of holes in the middle of the Nb plate, but the degree of relief is tiny. As shown in Fig. 12 (d), the damaged area of the surrounding-cut seam structure seems to be larger than that of the normal seam structure, but the overall damage is relatively reduced. The groove surrounding the brazed seam lessens the interaction between the Nb plate and the ceramic, thereby slightly reducing the strain experienced by the ceramic block. Since measurement of the damage parameters is difficult, the damage prediction method used in this paper can predict the easily damaged location in the brittle structure, offering valuable insights for actual scenarios.

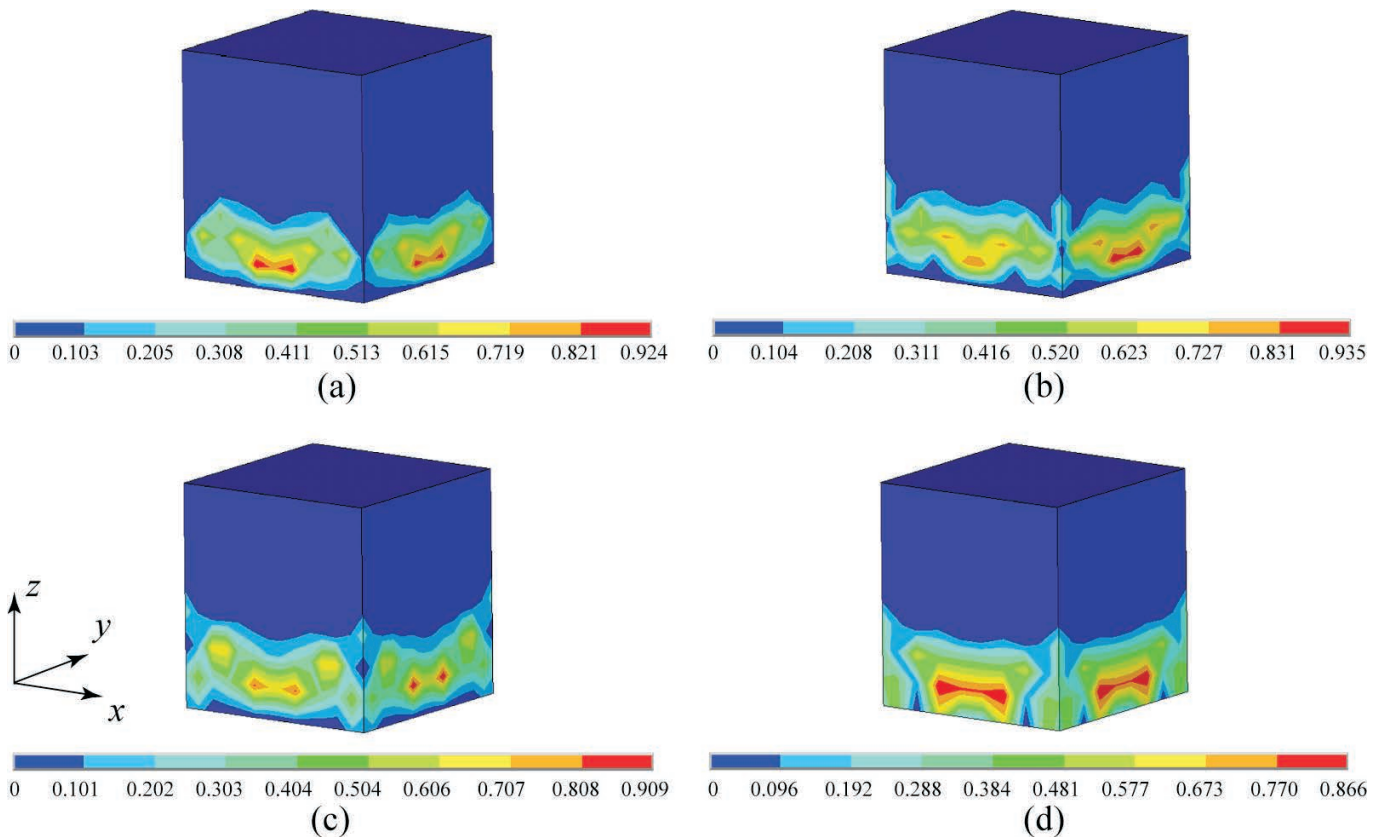


Fig. 12: Ceramic damage contour plots of different structures: (a) normal seam structure, (b) groove-type seam structure, (c) hole-type seam structure, and (d) surrounding-cut seam structure.

V. Conclusions

- (1) The seam shape of the brazed structure has an obvious influence on residual stress. In addition, the size adjustment of some specific positions also affects the strength of the brazed structure.
- (2) Residual stress near the brazing seam is extremely high, especially the stress on the brazing edge of the ceramic. Besides, the compressive stress near the seam is greater than the tensile stress.
- (3) The finite element analysis results show that, of the structures designed in our research for this paper, the surrounding-cut seam structure is the most appropriate for the $\text{Al}_2\text{O}_3/\text{Nb}$ structure. The optimum surrounding groove can significantly alleviate the residual stress at the bottom edge of the ceramic. Specifically, compared to the normal seam structure, the maximum tensile stress of the surrounding-cut seam structure with a groove width of 500 μm can be reduced by 29.5 %. Furthermore, proper removal of the filler from the seam edge can also reduce harmful residual stress.
- (4) Ceramic damage during brazing is simulated using ANSYS UPFs. Results indicate that the greatest damage occurs at the transition zone between the brazing position and the distal end. The damage is mainly related to the Z-direction stress in the ceramic. In comparison, the predictive value for damage in ceramic within the surrounding-cut seam structure is the lowest of the four structures.
- (5) Based on the conducted study, the surrounding-cut seam structure proposed in this paper shows superior performance in terms of both stress simulation and damage prediction.

References

- 1 Wang, J., Fang, F., An, H., Wu, S., Qi, H., Cai, Y., Guo, G.: Laser machining fundamentals: micro, nano, atomic and close-to-atomic scales, *Int. J. Extrem. Manuf.*, **5**, [1], 012005, (2023).
- 2 Xu, J., Zhang, G., Wang L., Wu C., Huang Y., Rong Y.: Study on the picosecond laser surface treatment and tribological properties of 3D woven carbon fiber reinforced carbon matrix (Cf/C) composites, *Compos. B Eng.*, **279**, 111463, (2024).
- 3 Monteiro, S.N., Louro, L.H.L., Gomes, A.V., Chagas, C.F.d.M., Caldeira, A.B., Lima Jr, É.P.: How effective is a convex $\text{Al}_2\text{O}_3\text{-Nb}_2\text{O}_5$ ceramic armor?, *Ceram. Int.*, **42**, [6], 7844–7847, (2016).
- 4 Patel, K.M., Pandey, P.M., Rao, P.V.: Study on machinability of Al_2O_3 ceramic composite in EDM using response surface methodology, *J. Eng. Mater. Technol.*, **133**, [2], (2011).
- 5 Wang, Y., Yang, Z.W., Zhang, L.X., Wang, D.P., Feng, J.C.: Low-temperature diffusion brazing of actively metallized Al_2O_3 ceramic tube and 5A05 aluminum alloy, *Mater. Des.*, **86**, 328–337, (2015).
- 6 Zewde, B.W., Admassie, S., Zimmermann, J., Isfort, C.S., Scrosati, B., Hassoun, J.: Enhanced lithium battery with polyethylene oxide-based electrolyte containing silane- Al_2O_3 ceramic filler, *ChemSusChem*, **6**, [8], 1400–5, (2013).
- 7 Zhang, X., Jeffrey, R.G.: The role of friction and secondary flaws on deflection and re-initiation of hydraulic fractures at orthogonal pre-existing fractures, *Geophys. J. Int.*, **166**, [30], 1454–1465, (2006).
- 8 Mir, F.A., Khan, N.Z., Parvez, S.: Recent advances and development in joining ceramics to metals, *Mater. Today: Proc.*, **46**, 6570–6575, (2021).
- 9 Moret, F., Eustathopoulos, N.: Ceramic to metal direct brazing, *Le Journal de Physique IV*, **03**, C7, C7–1043-C7–1052, (1993).
- 10 Galli, M., Botsis, J., Janczak-Rusch, J.: Relief of the residual stresses in ceramic-metal joints by a layered braze structure, *Adv. Eng. Mater.*, **8**, [3], 197–201, (2006).
- 11 Barrena, M.I., Gómez de Salazar, J.M., Gómez-Vacas, M.: Numerical simulation and experimental analysis of vacuum brazing for steel/cermet, *Ceram. Int.*, **40**, [7], 10557–10563, (2014).
- 12 Zhang, J., Wang, T., Liu, C., He, Y.: Effect of brazing temperature on microstructure and mechanical properties of graphite/copper joints, *Mater. Sci. Eng.: A*, **594**, 26–31, (2014).
- 13 Elrefaey, A., Tillmann, W.: Effect of brazing parameters on microstructure and mechanical properties of titanium joints, *J. Mater. Process. Technol.*, **209**, [10], 4842–4849, (2009).
- 14 Hernandez, X., Jiménez, C., Mergia, K., Yialouris, P., Mes-soloras, S., Liedtke, V.: An innovative joint structure for brazing Cf/SiC composite to titanium alloy, *J. Mater. Eng. Perform.*, **23**, [8], 3069–3076, (2014).
- 15 Zhang, J., Zhang, J., Li, L., Zhang, C., Zhang, Y., Lu, X.: Stress analysis of the brazing joints of tubular ceramic oxygen-permeable membranes and metal supports, *Ceram. Int.*, **45**, [2], 1545–1553, (2019).
- 16 Wang, T., Ivas, T., Lee, W., Leinenbach, C., Zhang, J.: Relief of the residual stresses in $\text{Si}_3\text{N}_4/\text{Invar}$ joints by multi-layered braze structure – experiments and simulation, *Ceram. Int.*, **42**, [6], 7080–7087, (2016).
- 17 Wang, S., Zhou, H., Kang, Y.: The influence of rare earth elements on microstructures and properties of 6061 aluminum alloy vacuum-brazed joints, *J. Alloy. Compd.*, **352**, 1–2, 79–83, (2003).
- 18 Jiang, W., Gong, J., Chen, H., Tu, S.T.: The effect of filler metal thickness on residual stress and creep for stainless-steel plate-fin structure, *Int. J. Press. Vessels. Pip.*, **85**, [8], 569–574, (2008).
- 19 Florjancic, M., Mader, W., Rühle, M., Turwitt, M.: Hrem and diffraction studies of an $\text{Al}_2\text{O}_3/\text{Nb}$ interface, *J. Phys. Colloques*, **46**, C4, C4–129-C4–133, (1985).
- 20 Mostaan, H., Abbasi, M.H., Karimzadeh, F.: Mechanochemical assisted synthesis of $\text{Al}_2\text{O}_3/\text{Nb}$ nanocomposite by mechanical alloying, *J. Alloy. Compd.*, **493**, 1–2, 609–612, (2010).
- 21 Scheu, C., Liu, Y., Oh, S.H., Brunner, D., Rühle, M.: Interface structure and strain development during compression tests of $\text{Al}_2\text{O}_3/\text{Nb}/\text{Al}_2\text{O}_3$ sandwiches, *J. Mater. Sci.*, **41**, [23], 7798–7807, (2006).
- 22 Sharma, P.K., Ambulkar, K.K., Parmar, P.R., Virani, C.G., Thakur, A.L., Joshi, L.M., Nangru, S.C.: Development of multi-channel high power rectangular RF window for LHCD system employing high temperature vacuum brazing technique, *J. Phys. Conf. Ser.*, **208**, (2010).
- 23 Zhao, Y., Wang, Y., Yang, Z., Wang, D.: Relief of residual stress in $\text{Al}_2\text{O}_3/\text{Nb}$ joints brazed with ag-cu-Ti/Cu/Ag-Cu-ti composite interlayer, *Arch. Civ. Mech. Eng.*, **19**, 1–10, (2019).
- 24 Wang, Y., Zhao, Y.T., Yang, Z.W., Wang, D.P.: Microstructure, residual stress and mechanical properties of $\text{Al}_2\text{O}_3/\text{Nb}$ joints vacuum-brazed with two Ag-based active fillers, *Vacuum*, **158**, 14–23, (2018).
- 25 Ding, W.-F., Zhu, Y.-J., Xu, J.-H., Fu, Y.-C.: Finite element investigation on the evolution of wear and stresses in brazed CBN grits during grinding, *Int. J. Adv. Manuf. Technol.*, **81**, 985–993, (2015).
- 26 Shen, X., Li, Y., Putchkov, U.A., Wang, J., Huang, W.: Finite-element analysis of residual stresses in $\text{Al}_2\text{O}_3\text{-TiC}/\text{W18Cr4V}$

- diffusion bonded joints, *Comput. Mater. Sci. Eng. A.*, **45**, [2], 407–410, (2009).
- ²⁷ Jeong, S.Y., Choi, Y.J., Park, P.: Parametric interpolation using sampled data, *Comput. Aided Des.*, **38**, [19], 39–47, (2006).
- ²⁸ Leinenbach, C., Weyrich, N., Elsener, H.-R., Gamez, G.: Al₂O₃- Al₂O₃ and Al₂O₃-ti solder joints-influence of ceramic metallization and thermal pretreatment on joint properties, *Int. J. Appl. Ceram. Technol.*, **9**, [4], 751–763, (2012).
- ²⁹ Niu, G.B., Wang, D.P., Yang, Z.W., Wang, Y.: Microstructure and mechanical properties of Al₂O₃ ceramic and TiAl alloy joints brazed with Ag-Cu-Ti filler metal, *Ceram. Int.*, **42**, [6], 6924–6934, (2016).
- ³⁰ Lee, K.N., Eldridge, J.I., Robinson, R.C.: Residual stresses and their effects on the durability of environmental barrier coatings for SiC ceramics, *J. Am. Ceram. Soc.*, **88**, [12], 3483–3488, (2005).
- ³¹ Zhou, B., Zeng, Z., Cai, Y., Feng, K.: FEM simulation and verification of brazing SiC ceramic with novel zr-cu filler metal, *Materials*, **12**, 3380, (2019).
- ³² Wibawa, L.A.N., Diharjo, K., Raharjo, W.W., Jihad, B.H.: The effect of fillet radius and length of the thick-walled cylinder on Von Mises stress and safety factor for rocket motor case. In: Proceedings of the International Conference on Science and Applied Science, Surakarta, Indonesia, AIP Publishing, July 7, 2020.
- ³³ Cabeza, S., Mishurova, T., Garcés, G., Sevostianov, I., Requena, G., Bruno, G.: Stress-induced damage evolution in cast Al-Si₁₂CuMgNi alloy with one- and two-ceramic reinforcements, *J. Mater. Sci.*, **52**, [17], 10198–10216, (2017).
- ³⁴ Zhao, Z.: Review of non-destructive testing methods for defect detection of ceramics, *Ceram. Int.*, **47**, [4], 4389–4397, (2021).
- ³⁵ Sfarra, S., Perilli, S., Paoletti, D., Ambrosini, D.: Ceramics and defects, *J. Therm. Anal. Calorim.*, **123**, [1], 43–62, (2015).
- ³⁶ Chakraborty, S., Islam, M.R.I., Shaw, A., Ramachandra, L.S., Reid, S.R.: A computational framework for modelling impact induced damage in ceramic and ceramic-metal composite structures, *Compos. Struct.*, **164**, 263–276, (2017).
- ³⁷ Fernández-Fdz, D., Zaera, R., Fernández-Sáez, J.: A constitutive equation for ceramic materials used in lightweight armors, *Comput. Struct.*, **89**, 23–24, 2316–2324, (2011).
- ³⁸ Zeng, G., Yang, X., Chen, L., Bai, F.: Damage evolution and crack propagation in semicircular bending asphalt mixture specimens, *Acta Mech. Solida Sin.*, **29**, [6], 596–609, (2016).
- ³⁹ Wang, S.Y., Sloan, S.W., Liu, H.Y., Tang, C.A.: Numerical simulation of the rock fragmentation process induced by two drill bits subjected to static and dynamic (impact) loading, *Rock Mech. Rock Eng.*, **44**, [3], 317–332, (2010).
- ⁴⁰ Bonora, N., Newaz, G.: Modeling damage evolution in a hybrid ceramic matrix composite under static tensile load, *J. Eng. Mater. Technol.*, **119**, [4], 401–407, (1997).
- ⁴¹ Ben Ramdane, C., Julian-Jankowiak, A., Valle, R., Renollet, Y., Parlier, M., Martin, E., Diss, P.: Microstructure and mechanical behaviour of a Nextel™610/alumina weak matrix composite subjected to tensile and compressive loadings, *J. Eur. Ceram.*, **37**, [8], 2919–2932, (2017).
- ⁴² Wang, S.Y., Sun, L., Yang, C., Yang, S.Q., Tang, C.A.: Numerical study on static and dynamic fracture evolution around rock cavities, *J. Rock Mech. Geotech. Eng.*, **5**, 4, 262–276, (2013).

