

Transition Analysis to Study the Effect of Cooling Rates on Thermal Stresses for Diffusion Bonded Joints

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Abstract

In this work the analytical and numerical methods were used to calculate the residual stresses induced in the joint due to the difference in the physical and mechanical properties of the materials, cooling from bonding temperature to room temperature. The residual stresses induced in graphite may become too high that the joint break down so it takes as major stress in the joint. It was found that the residual stress is affected by the joint geometry and the nickel interlayer thickness. The analytical calculation of the residual thermal stresses in graphite/Inconel 600 and Inconel 600/nickel interlayer/Graphite multilayered was done for bonding temperature $T_{\text{bond}}=800^{\circ}\text{C}$ with various nickel foil thickness, it found that increasing nickel thickness reduce the thermal residual stresses inside the graphite. Numerical method by FEM was used to estimate the distribution of the maximum residual stresses (first principle stress) in the joint. The results indicate that increasing nickel thickness reduces the maximum tensile residual stress. So the joint thicknesses with graphite (5 mm) /Ni (0.1-0.2)mm/ Inconel600 (5 mm) are convenient.

Introduction

The aim of modeling diffusion bonding can be of two folds; optimize the selection of the process variables (temperature, materials dimension, thermal expansion and cooling time) for a given material and also to provide an understanding of the mechanisms by which bonding is achieved [1]. Previous reviews in this area of modeling, the residual stresses induced after cooling in the joint were investigated [2-3].

In some cases investigate these thermal stresses are large enough to cause a degradation of strength by cracking of graphite or even failure of the joint. A more general approach is to solve the problem numerically using finite element calculations, general-purpose finite element software such as ANSYS package which was mostly adopted by [4]. The distribution of residual stress in graphite / graphite and graphite / metal joint is not uniform even a long the interface. Concentration of residual stress becomes more severe as the free surfaces approached [5].

Residual Thermal Stresses Analysis

Residual stresses that develop during cooling the simple metal/graphite strip geometries are calculated analytically. It was shown that these residual stresses depending on metal mechanical properties (behave elastically or plastically), the thickness of the

constituents, and the mismatch in thermal expansion. The bending strains in both materials are prescribed, by bending theory [5]. But they yield only very approximate results, since the temperature dependence of the materials properties and the metal plasticity are not taken in account [6]. The purpose of the residual stresses analysis is to assess the distribution, nature and level of the residual stresses in the ceramic as the thickness (decrease or increase in residual stresses) of dissimilar materials, the bonding parameters varies, in order to minimize these stresses for practical applications [6,7 and 8]. The selection of an appropriate method for measuring the bond strength is dictated by the purpose of testing, the bonding process, and bonding parameters. The mechanical quality of the bond can be monitored by both fracture mechanics and conventional testing method [4].

Numerical Analysis

In this work ANSYS program was used as a finite element method analysis to estimate the residual stresses values and distribution in the graphite/Inconel joint as well as using nickel interlayer with different thickness. The optimum bonding parameters should be estimated to minimize these stresses for practical applications. Calculations have been carried out with graphite/Inconel joint with Ni

interlayer, the diminutions of the samples used in this work as follows:

h1= graphite thickness (constant) = 5 mm

h2= Nickel thickness (variable) = (0.1-1) mm

h3= Inconel thickness (constant) = 5 mm

The analyses were done at bonding temperature 800°C for different cooling time periods; 3,6,9,12,15 and 18 min. A transient sequential coupled field analysis was used. These include thermal analysis followed by structural analysis. An 8-node, 3- Dimensional element (solid 97, then solid 45), were used. Inconel 600 physical and mechanical properties as a function o temperature have been determined [6, 9].

The variation of the coefficient of thermal expansion (α) with temperature (T) is given by:

$$\alpha(T)=-0.84 \times 10^{-12} T^2+5.58 \times 10^{-9} T+11.65 \times 10^{-6} \dots\dots\dots(1)$$

The variation of the elastic modulus (E) with temperature (T) is given by:

$$E(T)=-7.97 \times 10^{-6} T^2-59.41 \times 10^{-3} T+206.55 \dots\dots\dots(2)$$

Where E in GPa and T in °C

The physical and mechanical properties of graphite have been determined from ref. [10]. The physical and mechanical properties of nickel have been determined from ref. [11, 12]. Plastic deformation of nickel interlayer plays an important role in relieving residual stress in the joint. Thus the plastic deformation, recovery, and creep of nickel interlayer are taken into account. The power law creep equation was used to estimate the Ni creep behavior, as in equation (3) [13].

$$\dot{\epsilon}_c = S.L^2.D.(\sigma_c/E)^n \dots\dots\dots(3)$$

Where

$\dot{\epsilon}_c$ is creep rate, h^{-1} , S is constant(10^{29}) cm^{-4} , L is grain diameter, cm, D is self diffusion coefficient, cm^2/s , σ_c is creep stress, MPa, E is modulus of elasticity, MPa and n constant (3-7). In general graphite are much weaker in tension than in compression. Graphite/ metal joint fail at the locations where residual stress concentrations are high, which are often in graphite parts near the interface. The maximum value of the first principal stress (σ_{1max}) which is usually located near the edge of the interface in graphite side was taken as the major comparison factor in this work.

The joint geometry has a great effect on the stress distribution within graphite and Inconel. However in this work the effect of Ni thickness on the stress distribution in graphite was considered only because graphite are the weakest part of the joint.

Equation (4) is used to calculate the residual stresses in graphite. The thickness of the graphite and Inconel layer were assumed to be constant.

For graphite /nickel/ Inconel joint the maximum σ_x can be expressed as follows [14].

$$\alpha_{ix}(Z_i) = E'_i(\alpha' - \alpha_i) + (Z_i - Z'_i)/R' \Delta T \dots\dots\dots(4)$$

Where

$$1/R' = 1/R \Delta T \dots\dots\dots(5)$$

$$1/R = E'_2(\alpha' - \alpha_2) h_1 h_2 + E'_3(\alpha' - \alpha_3) h_3 (h_{12} + h_{23}) - \Delta T/E'_2 Z'_2 h_2 h_{12} + E'_3 Z'_3 h_3 (h_{12} + h_{23}) -$$

$$1/12 \sum_{i=1}^3 E'_i h_i^3 \dots\dots\dots(6)$$

$$E'_i = E_i / (1 - \nu_i) \dots\dots\dots(7)$$

Where: E_i refers to the modulus of elasticity for each layer, E'_i refers to the plain modulus of elasticity or each layer, ν_i refers to the poisson's ratio for each layer, α_i refers to the thermal expansion coefficient for each layer, α' refers to the compensation joint thermal expansion coefficient.

Results and Discussions

Transient Finite element method of Inconel 600 / Graphite diffusion bonded joints

1-For all joints, the increase in maximum principal stress with increasing cooling time was observed and this is due to the fact that, when we relate the time of recrystallization to the recrystallization temperature, we observe an Arrhenius behavior as shown in Fig. (1 and 2). this is expected, due to atom movement, governs the reaction, and this in turn, are dependent on thermal activation [15]:

$$\ln t = C+B/T \dots\dots\dots(8)$$

Where C and B are constant, t, time (s) and T, temperature (0K), we recognize that a fast reaction rate R(a short time,since $R = 1/t$) correspond to rapid diffusion:

$$\ln R = \ln R_o - E/KT = -\ln t \dots\dots\dots(9)$$

Where C and B of equation (8) are $\ln R_o$ and E/K , respectively.

2- The maximum value of tensile stress (using transient thermal analysis) along all joints appeared at Inconel / graphite joints and

equal to (914MPa) at 18min. cooling time and this result almost agrees with previous study of joining graphite to Inconel 718, see Fig. (2) [16].

- 3- For all joints, the maximum value of tensile stress using transient thermal analysis is lower than that of static analysis for (3-12) min. cooling range and this is related to introducing the elastic and plastic creep which is decreases with increasing cooling time [17], see Figs.(3-12).
- 4- When cooling range exceeds 12 min., the maximum tensile stress increases markedly with increasing cooling range as shown in Figs. (13-14).
- 5- For interlayer thickness(0.1-0.2) mm , the tensile stress using transient analysis is lower than that of static analysis that gives a reliable joint at room temperature, and this is agrees well with experimental study of joining Inconel to graphite using nickel interlayer [18].
- 6- Compressive stresses show a similar behavior with tensile stresses of increase with cooling time, this could observe for all modeled diffusion bonded joints as shown in Fig.(1).

For 1 mm nickel interlayer the maximum compressive stress is almost equal to a previous study of joining nickel to graphite experimentally [19].

Conclusions

Inconel 600 was bond to graphite using transient axisymmetric finite element analysis by using (ANSYS) program to study the effect of cooling rate on thermal stresses induced in direct joining of Inconel/ graphite as well as for joining of these two base materials with introducing nickel interlayer during cooling to room temperature. Transient Axisymmetric finite element analysis reveals the following:

- 1- For all joints, the increase in maximum principal stress with increasing cooling time was observed and this is due to the fact that, when we relate the time of recrystallization to the recrystallization temperature.
- 2- The maximum value of tensile stress (using transient thermal analysis) along all joints appeared at Inconel/ graphite joints
- 3- For all joints, the maximum value of tensile stress using transient thermal analysis is lower than that of static analysis for (3-12) min. cooling range.
- 4- When cooling range exceeds 12 min., the maximum tensile stress increases markedly with increasing cooling range.
- 5- For interlayer thickness (0.1-0.2) mm, the tensile stress using transient analysis is lower than that of static analysis that gives a reliable joint at room temperature.
- 6- Compressive stresses show a similar behavior with tensile stresses of increase with cooling time; this could observe for all modeled diffusion bonded joints.

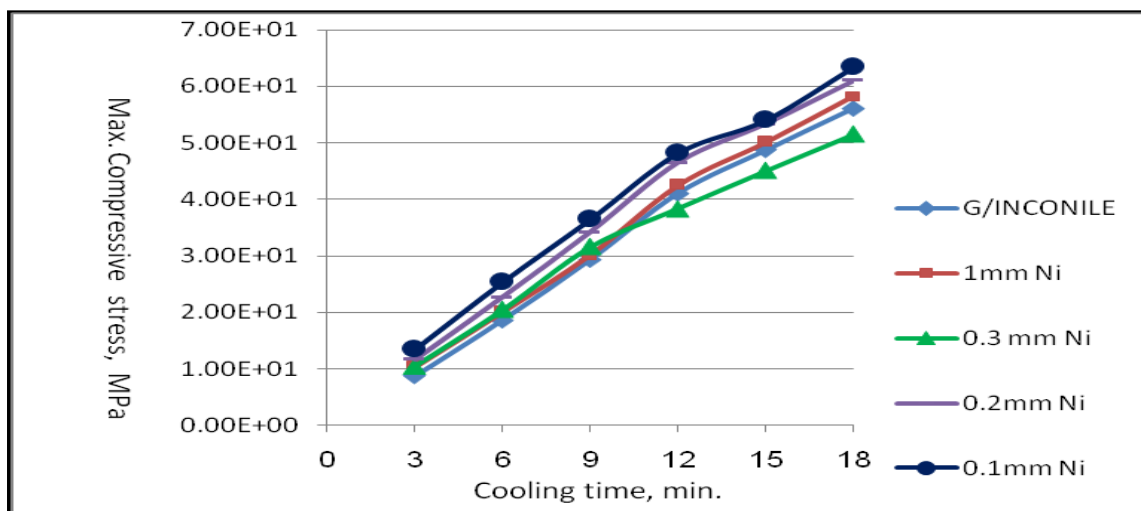


Fig. (1) Max. compressive stress distribution on the surface of graphite/ Inconel 600 joint at 800 °C diffusion bonding temperature using different Ni interlayer thickness.

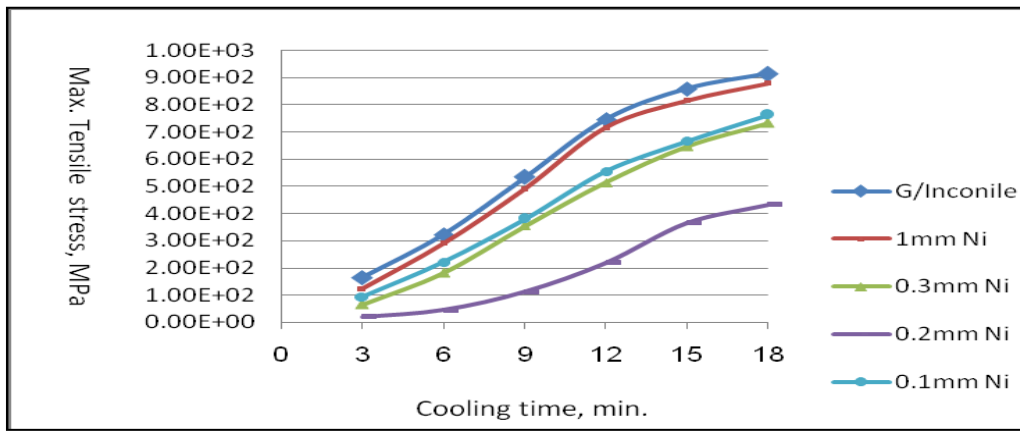


Fig. (2) Max. tensile stress distribution on the surface of graphite/ Inconel 600 joint at 800 °C diffusion bonding temperature using different Ni interlayer thickness.

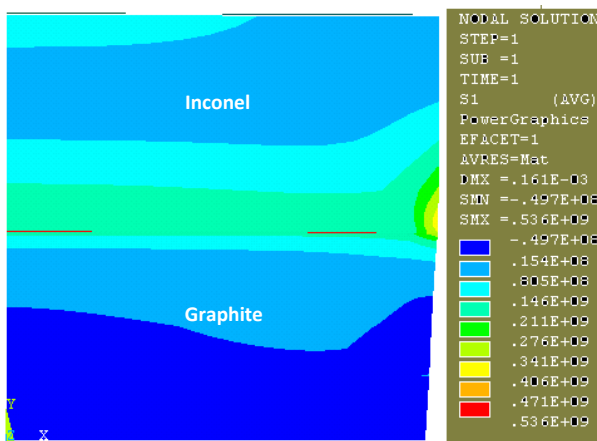


Fig. (3) Three dimensions principal stress distribution across Inconel 600/Graphite diffusion bonding joint using static analysis.

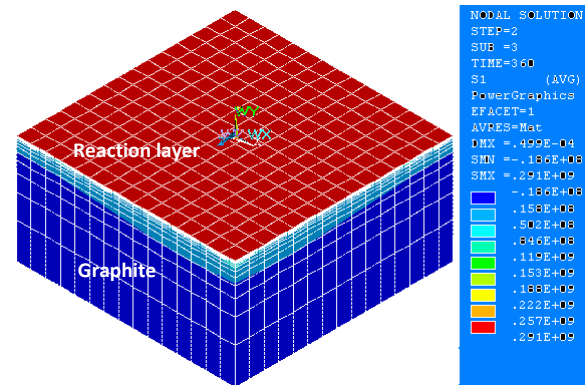


Fig. (5) Three dimensions principal stress distribution across Inconel 600/Graphite diffusion bonding joint using transient analysis for 6 min. cooling time.

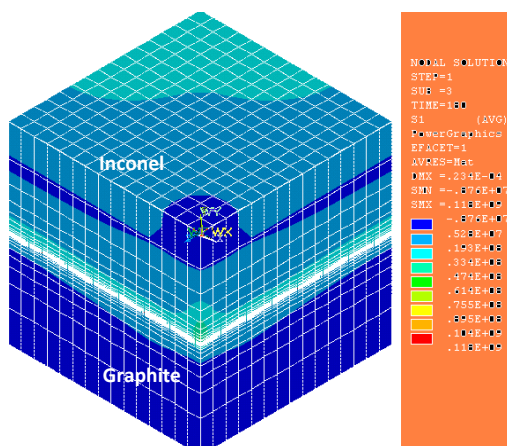


Fig. (4) Three dimensions principal stress distribution across Inconel 600/Graphite diffusion bonding joint using transient analysis for 3 min. cooling time.

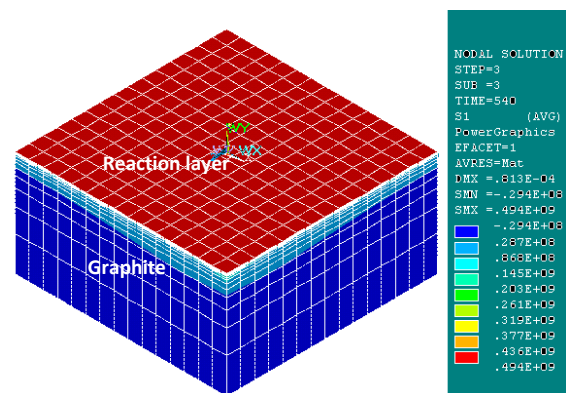


Fig. (6) Three dimensions principal stress distribution across Inconel 600 / Graphite diffusion bonding joint using transient analysis for 9 min. cooling time.

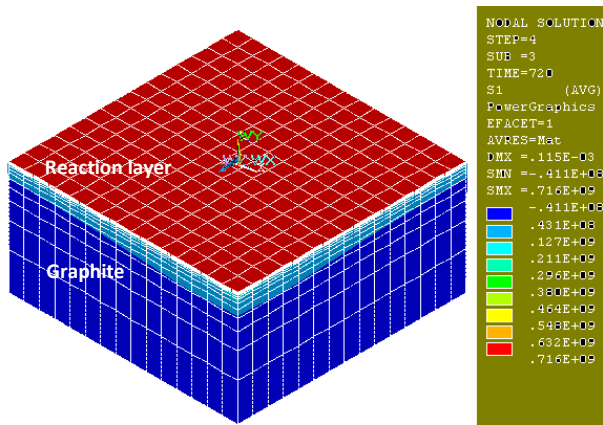


Fig. (7) Three dimensions principal stress distribution across Inconel 600 / Graphite diffusion bonding joint using transient analysis for 12 min. cooling time.

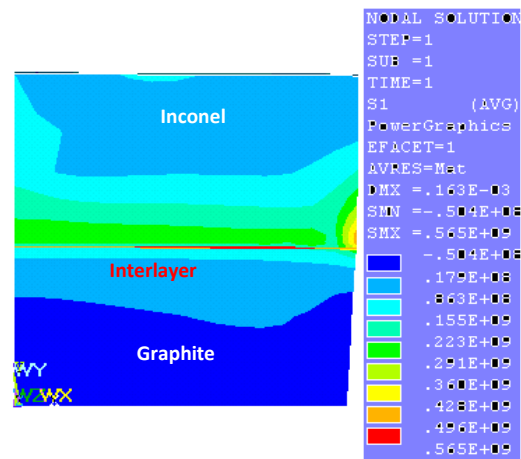


Fig. (10) Three dimensions principal stress distribution across the diffusion bonding joint using 0.2 mm Ni interlayer thickness using static analysis.

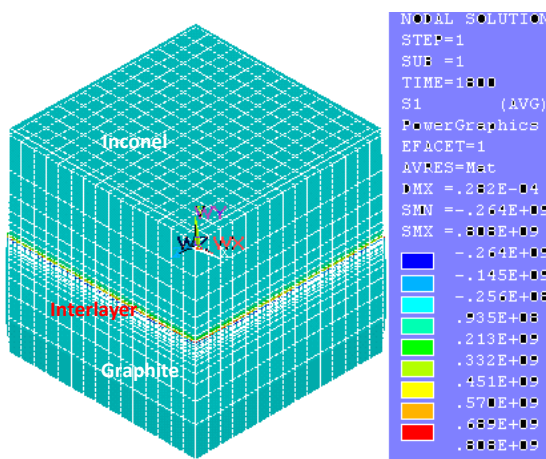


Fig. (8) Three dimensions principal stress distribution across the diffusion bonding joint using 0.1 mm Ni interlayer thickness using static analysis.

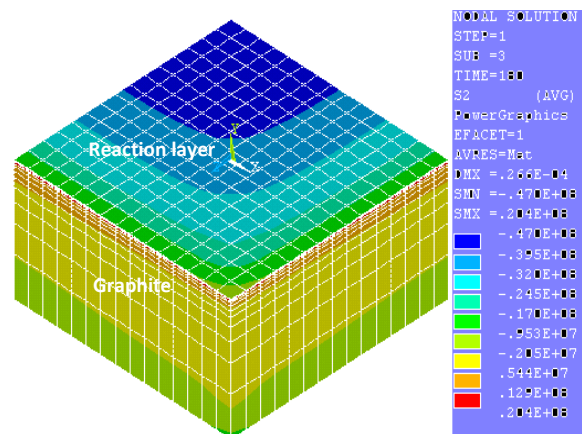


Fig. (11) Three dimensions principal stress distribution across the diffusion bonding joint using 0.2 mm Ni interlayer thickness using transient analysis for 3 min. cooling time.

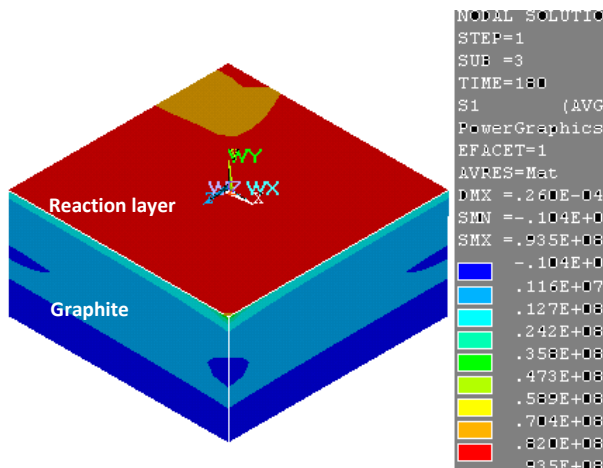


Fig. (9) Three dimensions principal stress distribution across the diffusion bonding joint using 0.1 mm Ni interlayer thickness using transient analysis for 3 min. cooling time.

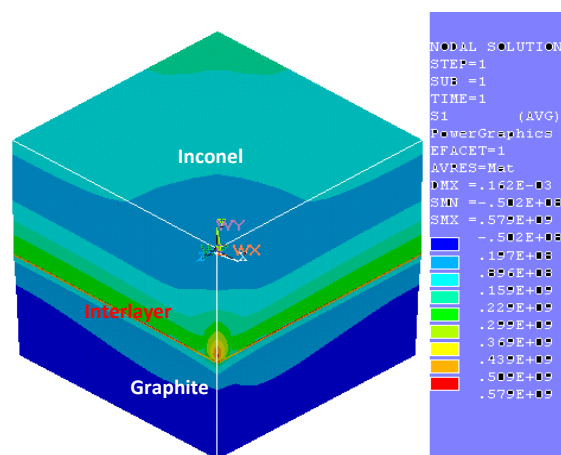


Fig. (12) Three dimensions principal stress distribution across the diffusion bonding joint using 0.3 mm Ni interlayer thickness using static analysis.

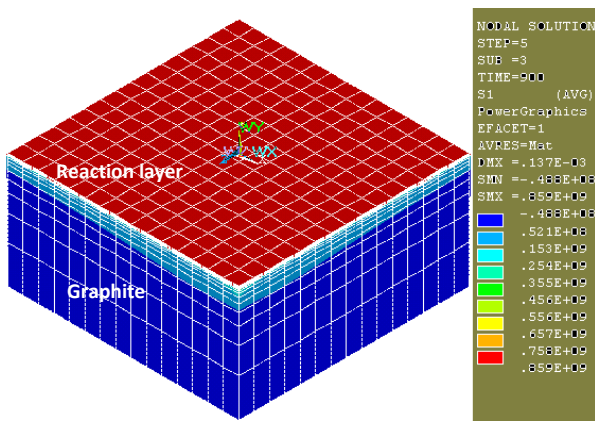


Fig. (13) Three dimensions principal stress distribution across Inconel 600 / Graphite diffusion bonding joint using transient analysis for 15 min. cooling time.

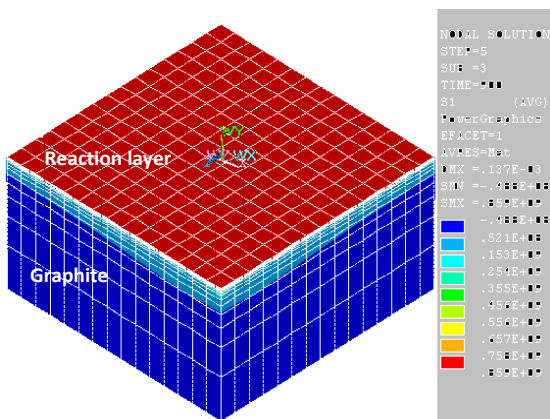


Fig. (14) Three dimensions principal stress distribution across the diffusion bonding joint using 0.1 mm Ni interlayer thickness using transient analysis for 15 min. cooling time.

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الخلاصة

يتضمن البحث دراسة الاجهادات المتبقية في وصلة اللحام وخاصة أثناء التبريد من اختلاف الخواص الفيزيائية والميكانيكية لمواد المزمع ربطها في الوصلة، وقد تكون هذه الاجهادات عالية لدرجة تؤدي الى تكسر الكرافيت وفشل وصلة اللحام بعد انتهاء التبريد أو الى الفشل أثناء الاستخدام. لذا تم اعتماد قيم الاجهادات المتبقية في الكرافيت كأهم الاجهادات المتبقية في وصلة اللحام ولمقارنة تأثير المتغيرات المستخدمة في التحليل النظري للاجهادات الحرارية الناتجة عن اللحام في درجة حرارة ($T_{bond}=800^{\circ}C$) لوصلة أنكونل مع الكرافيت بالإضافة الى استخدام رقائق من النيكل النقي المختلفة السمك وجد أن قيم الاجهادات المتبقية تقل مع زيادة سمك النيكل. استخدمت طريقة العناصر المحددة (FEM) في التحليل العددي لقيم الاجهادات المتبقية ولتخمين توزيعها فيوصلة اللحام. استخدم الاجهاد الأساسي الأول (first principle stress) كقيمة مقارنة بين النتائج المستحصلة من هذه التحاليل. أظهرت النتائج أن أعلى قيمة للاجهاد الأساسي الأول في الكرافيت يقل مع زيادة سمك النيكل لذا وصلة اللحام بالأبعاد (0.1- graphite(5mm)\Ni (0.2mm)\Inconel600 (5mm) تعتبر مناسبة.