COMPARISON STUDY OF JOINING Ni-ALLOY WITH GRAPHITE

Awfa Abdul-Rassol Abdullah
Department of Applied Science, University of Technology.

Abstract

Modeling of diffusion bonding of Inconel 600 /Pyrolytic Graphite and Inconel 600/steel interlayer/Pyrolytic Graphite is investigated in this research. Modeling implies utilization of ANSYS package to predict axisymmetric thermoelastic finite element analysis from the above materials. The model is used; to calculate thermal stresses induced across diffusion bonded joints. Investigating thermal stress levels along the potential failure interface for both joints is extremely helpful; these residual stresses are mostly the forces of joint failure for both joints. Axisymmetric finite element analysis involves applying temperature along the whole joint as main parameter; the second parameter was changing the steel interlayer.

Introduction

Diffusion bonding can be used to join over 730 pairs of dissimilar materials. Over the last four decades, there has been a real need for special purpose structural materials, which can be loaded for a long period of time, at a very high temperature. Such materials have been required to be used in special engineering applications, like aerospace (thermal management devices for missiles, liquid rocket engines, and space surveillance) and nuclear industries (nuclear fusion reactor) where very difficult conditions have to be accommodated by the materials used [1]. The metals used in ceramic-to-metal joints are selected largely on the basis of the joint configuration and the service requirements. The most commonly used metals are low – and medium alloy steels, copper alloys, nickel alloys and the refractory metals [2]. The base materials in this research is Inconel 600 and pyrolytic graphite, they are used in combination due to their outstanding high temperature strength in sever environment. Engineering developments have changed not only the nature of the graphite/Inconel interest, but also the performance engines, which may have to stand with both high stresses and high temperature. The objective of this work is to develop a model using ANSYS program. This program employs thermal and mechanical solution. Neglecting the thermal solution comes as a result from the heat transfer calculation, which gives that, the weldement joint could be assumed as a lumped system (no thermal gradient across the diffusion bonding weldement). Concentration of residual stress becomes more severe as the free surfaces approaches. Essential problems in solid state bonding are summarized [3]:

1. Bonding strength at joining interface.
2. Thermal stresses.

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 the fracture mechanics and conventional testing method [4].We focused our attention on thermal stresses across the joint; the thermal stresses may be influenced by the resulting microscopic changes in thermal expansion coefficient, modulus of elasticity and poisson’s ratio.

Residual Stresses

Outline of residual stresses

Modern structures very often require components of high strength as well as sufficient ductility and resistance against abrasive wear and high temperatures [5, 6]. In cases where these requirements cannot be satisfied by monolithic conventional materials, it can be useful to employ brazed ceramic / metal compounds [7]. During cooling down from joining temperature, such compounds develop a complex residual stress state depending on the differences in the thermal expansion behavior, the elastic and plastic properties of the components, geometrical, and cooling conditions [8]. The distribution of residual stresses in a graphite/metal weldement is not uniform even along the interface. Concentration of residual stress becomes more severe as the free surfaces approaches. The maximum tensile stress concentrates on or near the interface and the free surfaces [3]. A relationship between principle stresses induced in the joint and bonding temperature using different steel interlayer thickness were estimated. Principal stresses that lead to joint failure, are tensile stresses induced in the graphite joint interface as well as in graphite material. Optimum diffusion bonding parameters will be predicted with the aid of finite element analysis.

In cases where these requirements cannot be satisfied by monolithic conventional materials, it can be useful to employ brazed ceramic/metal compounds [7]. During cooling down from joining temperature, such compounds develop a complex residual stress state depending on the differences in the thermal expansion behavior, the elastic and plastic properties of the components, geometrical, and cooling conditions [8]. The distribution of residual stresses in a graphite/metal weldement is not uniform even along the interface. Concentration of residual stress becomes more severe as the free surfaces approaches. The maximum tensile stress concentrates on or near the interface and the free surfaces [3]. A relationship between principle stresses induced in the joint and bonding temperature using different steel interlayer thickness were estimated. Principal stresses that lead to joint failure, are tensile stresses induced in the graphite joint interface as well as in graphite material. Optimum diffusion bonding parameters will be predicted with the aid of finite element analysis.

Residual thermal stresses analysis

The aim of modeling diffusion bonding can be regarded as two folds; to optimize the selection of the process variables for a given material and also to provide an understanding of the mechanisms by which bonding is achieved [9] a large stress concentration may be introduced in the joint during the cooling to room temperature as a result of thermal expansion mismatch between the dissimilar materials. Previous reviews in this area of modeling the residual stresses induced after cooling in the joint were investigated [10-11].

In some cases unfortunately these thermal stresses are large enough because 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 program were mostly adopted [12]. 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 sever as the free surfaces approached.

Experimental Work

Axisymmetric finite element method seems to be superior for checking the localized stress concentration in diffusion bonded joint. Therefore finite element method was used, for a rough estimation of induced residual thermal stress in Pyrolytic Graphite/Inconel 600 joints. In the present study, a finite element method was adopted to calculate the residual stresses (principle stresses) induced in the joint. The most dangerous stresses are tensile stresses in graphite near the joint; these residual stresses come as a result of the thermal expansion mismatch during cooling. The thermal expansions of most metals are much higher than graphite[13]. As a result cooling to room temperature must be slow enough to avoid the joint failure. Investigating stress levels along the potential failure interfaces is extremely helpful; these residual stresses are the forces of the joint failure [14]. Creating a finite element model with ANSYS is illustrated by selecting the correct element type is very important part of the analysis process. In this research it was appropriate to choose a three dimension solid element. First the analysis was performed on the joint in which reaction layer is absent near the joining interface of Inconel/graphite. Second, assuming that the reaction layer containing a composite properties. The model geometry for Inconel / graphite joint consist of three volumes, (Inconel 600, reaction layer, graphite) [15,16]. For Inconel / steel interlayer/ graphite joint the model geometry consist of five volumes, (Inconel 600, reaction layer, steel interlayer, reaction layer, graphite)

[17,18]. In this investigation the properties of the reaction layer were assumed to have average properties between adjacent materials at interface [3]. See Table (1 and 2).

The applied loads are the most important options, for most engineering problems these options could be classified into:

1. Structural Problems: the related options are; displacement, forces, distributed loads (pressure, temperature for thermal expansion).
2. Thermal Problems: the related options are; temperature, heat transfer rates and convection surfaces.

In this research, diffusion bonding process includes two problems; structural for applying bonding pressure and thermal problem for heating process (applying bonding temperature). The structural solution was achieved after solving the heat transfer problem through bonded joints (the system was considered uniform in temperature). This type of analysis is called the lumped heat capacity method, were smaller the physical size of the specimen, the more realistic the assumption of a uniform temperature throughout. Such an analysis may be expected to yield reasonable estimates when the following condition is met [19]: -

$$\frac{h\left(\frac{V}{A}\right)}{K} \langle\ 0.1 \quad \text{...} \quad (1)$$

Where h is the convection heat – transfer coefficient (W/ m^2. C°) at all specimen outside surfaces, V is the sample volume (m^3) and K is the thermal conductivity of the solid sample (W/m. C°), A is the surface area(m^2). The calculations for lumped system assumption are described below [19,15].

We assume that:

$$\frac{h\left(\frac{V}{A}\right)}{K} = 0.1 \Rightarrow h = 0.1 \times K\left(\frac{A}{V}\right), k = 14.9$$

W/m.C°for Inconel, $A=2x10^{-4}m^2$,$V=0.5x10^{-3}m^3$

$h = 0.1 \text{ x } 14.9/0.25x10^{-2} = 1.49/ 0.25 \text{ x}10^{-2} = 596$, $h = 596$ ($W/m^{2\cdot}C$) It means that the h value must not exceed 100. While h is much bigger to satisfy the lamp system condition (Biot number < 0.1), it means that there is no thermal gradient through the diffusion bonded joints.

Results and Discussions

Finite element analysis of Inconel 600 / Graphite diffusion bonded joints

In this investigation a stimulated model for diffusion bonded joints of Inconel 600/Graphite was introduced. Thermal stresses induced in the diffusion bonded joints were examined using ANSYS program. Axisymmetric finite element method using ANSYS program seems to be superior for checking the localized stress concentration induced in the joint after cooling. In the present, we postulate the bonding at interface with considering a reaction layer of 10 μm thickness at graphite / Inconel 600 interfaces. The concentration of thermal stresses on the surface near the joining interface resulted in a fine division of element near the joining interfaces. It was assumed that the physical properties of Inconel 600 and steel interlayer are changed with hanging temperature in this analysis. Fig.(1 and 2)show the principle stress distribution through assembly without and with introducing reaction layer when the applied thermal load is 800 C°, assuming that the cooling of joint from bonding temperature to 100C°. It was noticed that the strain in the joint was not uniform through assembly, for all joints the maximum tensile stress (maximum principle stress) appeared in the graphite near joining interface about 536 MPa when direct joining of graphite to Inconel 600 as shown in Fig.(2). Generally tensile thermal stresses induced in the reaction layer and graphite, whereas compressive thermal stresses induced in Inconel 600 as shown in Fig. (2), compared with when there is no reaction layer, the magnitude of maximum tensile stress in graphite is not significantly different but it position approaches closer to joining interface as shown in Fig. (1), this correspond well to the fact that fracture on bending test occurred very close to joining interface [20].

Finite element analysis of Inconel 600 / steel /Graphite diffusion bonded joints

In this investigation a stimulated model for diffusion bonded joints of Inconel 600 /steel alloy/Graphite using (0.1, 0.2, 0.3 and 1 mm) interlayer thickness was introduced. Thermal stresses induced in the diffusion bonded joints were examined using ANSYS program. Figs. (3 through 6 shows the principle stress distribution through assembly when the applied thermal load is 800 C°, assuming that the cooling of joint from bonding temperature to 100 C° for different steel interlayer thickness (1, 0.3. 0.2, 0.1 mm).

It was noticed that the strain in graphite /steel/Inconel joint was not uniform through assembly. The maximum principle stress appeared in the graphite near joining interface about (499 MPa) when interlayer thickness is 1 mm as shown in Fig. (3). The maximum principle stress appeared in the graphite near joining interface about (504 MPa) when interlayer thickness is 0.1 mm as shown in Fig. (4). For interlayer (0.2mm) the maximum principle stress appeared in the graphite near joining interface (507 MPa), we also observe a drastic increase in compressive stress near graphite joint. For all joints the maximum tensile stress (647MPa) appeared near free surfaces of graphite for interlayer thickness (0.2 mm) as shown in Fig.(5). For the above results the amount of stress is far beyond the shear strength of graphite. Because graphite are much weaker in tension than in compression, the residual tensile stresses in the specimen can be expected to result in localized stresses.

Therefore it is thought that cracking in graphite will easy initiate during cooling to room temperature. For steel interlayer thickness 0.3 mm, the principle stress also shows no compressive stresses across the joint, this is may be related to the decrease in elastic modulus with increasing bonding temperature, as shown in Fig.(6). This behavior is similar to a previous study of diffusion bonding of graphite to steel [21], were as the maximum tensile stress for this joint is (525 MPa). The maximum principle stresses induced in graphite interface at all joining temperature have it lower limit at 0.1 mm interlayer thickness. The solubility of carbon is grater than that of ferrite. Therefore, when the graphite /steel couple is heated to a temperature at which austenite exists in the microstructure of steel, diffusion bonding may be possible due to remarkable diffusion of carbon atom from graphite to austenite [22]. This explains why good joint was obtained at temperature higher than lower critical line A1 [23].

Effect of interlayer thickness on induced principle stresses of diffusion bonded joints

As mentioned earlier, it is common for some form of strain reliving to be used when joining ceramics to metals at high temperature. Finite Element Analysis could be used to examine the effect of interlayer thicknesses on thermal stress during cooling from bonding temperature using different steel interlayer thicknesses (1, 0.3, 0.2, and 0.1 mm). Mostly tensile thermal stress was induced in graphite, whereas compressive thermal stress was induced in steel and Inconel 600. Fig. (7), shows thermal stress distribution the Z- axis direction on the surface of the joint obtained by annealing at 800C°. The maximum tensile thermal stress in graphite is located near the graphite/steel interface and near free surfaces of Inconel 600 for (0.1,0.2,1) mm and for direct bonding of inconel to graphite as shown in Fig.(7). The purpose of the present study is to examine the effects of introducing steel interlayer as well as the effect of interlayer thickness on residual stress and fined the critical thickness for applicable joint as well as the effect of interlayer thickness on residual stress and fined the critical thickness for applicable joint. It was noticed that for direct joining and for steel interlayer thickness 1 mm, the maximum compressive stress are the same (502 MPa), This behavior is similar to a previous study of diffusion bonding of graphite to steel [23]. This is likely due to a more pronounced difference between room temperature and heating temperature.

For direct joining of inconel to graphite, maximum tensile stress (536 MPa) is located at graphite/steel interface. For interlayer thickness 1mm the maximum principal tensile stress (502 MPa) appeared near graphite steel interface at graphite side. It also noticed that, for steel interlayer thickness 0.2 mm, the residual stress increased rabidly from tensile to compressive stress across the joint interface, this will evenly initiate cracks easily at room temperature. This is likely due to a more pronounced difference between room temperature and heating temperature. For steel interlayer thickness 0.3 mm, the principle stress also shows no compressive stresses through graphite and near the joining interface, it leads to that, there is no fluctuation of changing the principles stress type, therefore those joints are expected to be stable at room temperature. For interlayer thickness 0.1 mm the maximum tensile stress is the highest for all joints (852 MPa) at graphite/steel interface.

Conclusions

Inconel 600 was bond to graphite using axisymmetric finite element analysis by using (ANSYS) program to study thermal stresses induced in direct joining of Inconel/ graphite as well as for joining of these two base materials with introducing steel interlayer during cooling to room temperature.

Axisymmetric thermoelastic finite element analysis reveals the following:

1- For direct bonding the maximum compressive stress is equal to(647MPa) appeared near free surfaces of graphite for interlayer thickness0.2 mm and maximum tensile stress is near joint interface as well as for Inconel/ steel interlayer/ graphite joint except for interlayer thickness 0.3 mm. So these joints expected to be not stable at room temperature were crack initiate easily due to the high tensile stress.

2- Generally tensile thermal stresses induced in the reaction layer and graphite, whereas compressive thermal stresses induced in Inconel 600, compared with when there is no reaction layer, the magnitude of maximum tensile stress in graphite is not significantly different but it position approaches closer to joining interface .

3- For Inconel 600/ steel interlayer/graphite diffusion bonded joints, all joints shows high compressive stress except for 0.3 mm interlayer thickness, shows no compressive stress along the joint.

4- Bonded joint for interlayer thickness 0.1 mm shows the highest tensile stress along the joint and this is due to increase of thermal expansion with increasing the applied temperature(low interlayer thickness).

5- Bonded joint for interlayer thickness 0.2 mm shows a fluctuation in thermal stresses at graphite/ steel and steel/ Inconel interfaces, so this joint expected to fail during cooling to ambient temperature.

6- Bonded joint for interlayer thickness 1 mm shows tensile stress peaks along graphite/ steel interlayer/ Inconel 600 joints, the maximum tensile stress value are almost equal to the estimated results for direct joining of Inconel 600/graphite.

7- Optimum results for direct joining of Inconel 600/graphite and with introducing steel interlayer with different thickness for Inconel/Graphite base materials were observed for interlayer thickness 0.3 mm where this joint shows no tensile stress along Z-axis which is have the most dangerous effect during cooling to room temperature. The estimated values of compressive stress along interface and across the joint show it lowest value. Therefore it expected to meet the feasibility of critical thickness for joining Inconel 600 to pyrolytic graphite using steel interlayer.

Table (1)

Constant value for each material for Inconel/Graphite joint.

Constant	*graphite*	*interlayer*	*Inconel 600*
E GPa	4.8	105.9	207
$\alpha x10^{-6}/k^{o}$	3	8.5	13.3
μ	0.26	0.27	0.28

Table (2)
Constant values for each material for Inconel/steel interlayer/Graphite joint.

Constant	*graphite*	*Interaction layer*	*Steel interlayer*	*Interaction layer*	*Inconel 600*
E GPa	4.8	104.16	203.55	205	207
$\alpha x10^{-6}/k^{o}$	3	7.35	11.7	12.3	13.3
μ	0.26	0.27	0.28	0.27	0.28

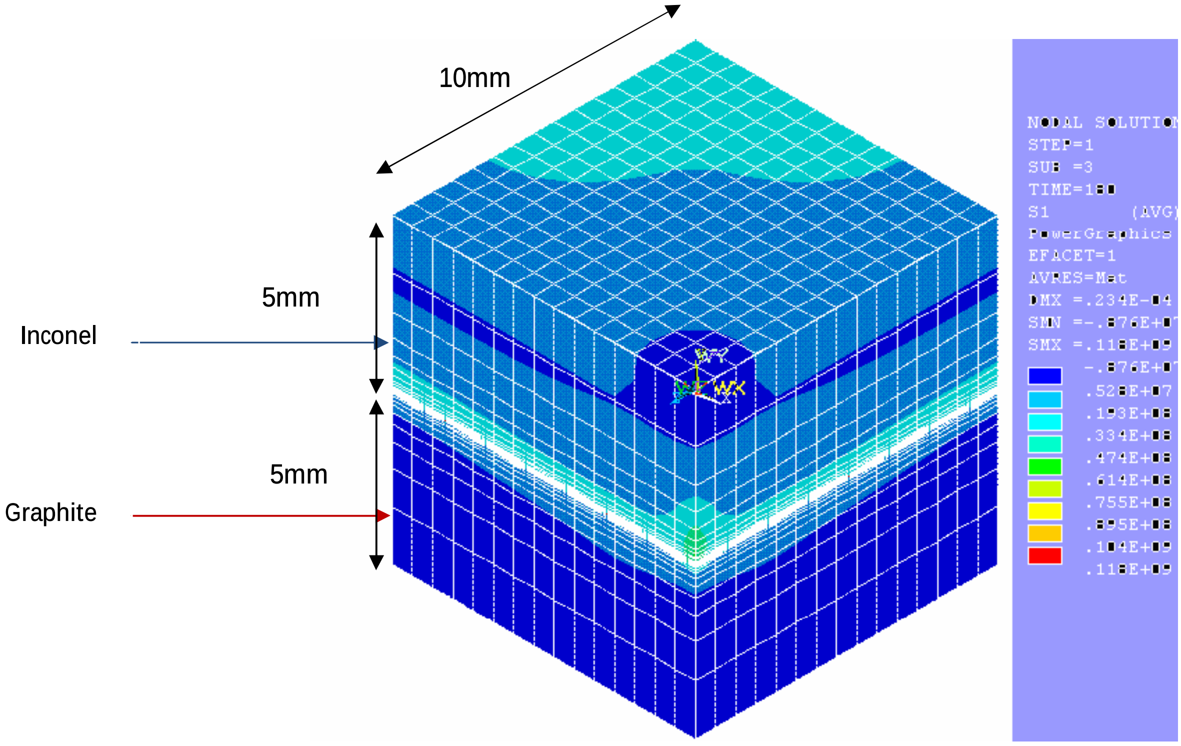

Fig. (1) : Three dimensions principal stress distribution across Inconel 600 / Graphite diffusion bonding joint.

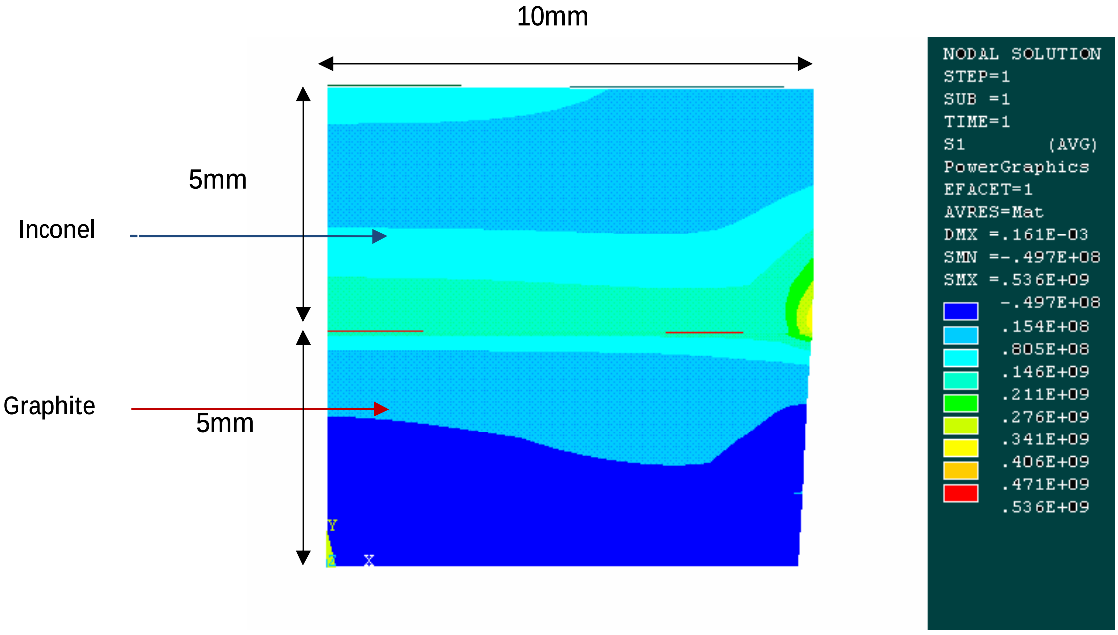

Fig. (2) : Two dimensions principal stress distribution across Inconel 600 / Graphite diffusion bonding joint with introducing reaction layer.

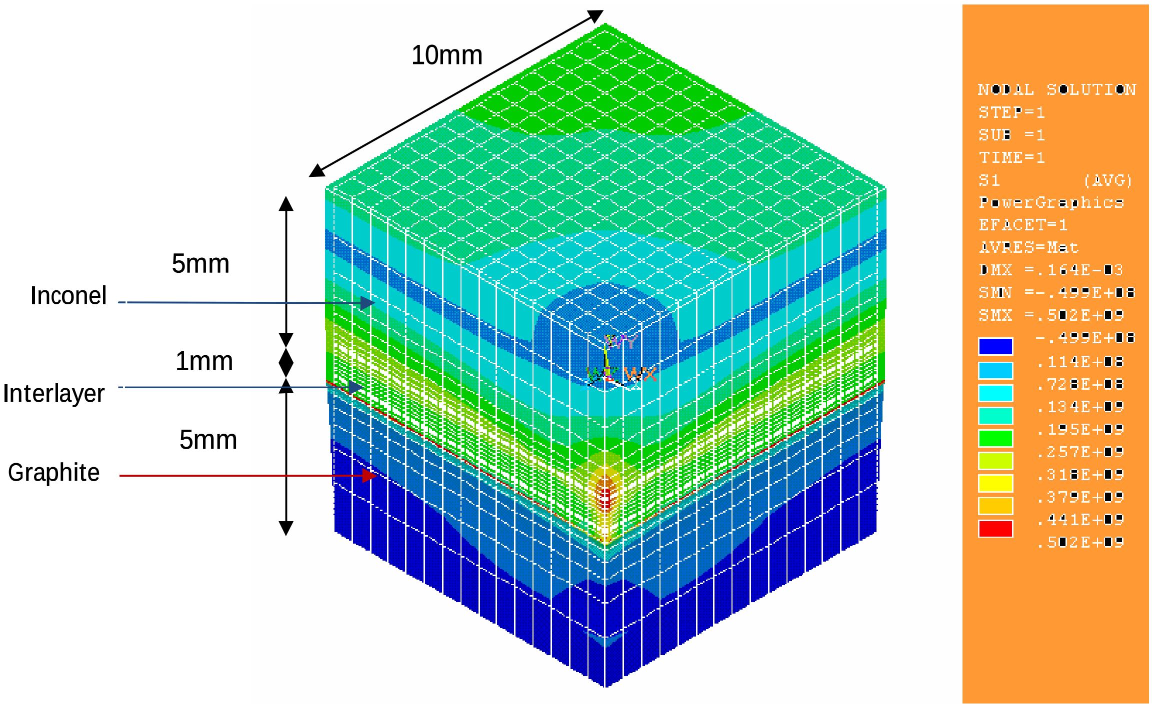

Fig. (3): Three dimensions principal stress distribution across the diffusion bonding joint using 1 mm steel interlayer thickness.

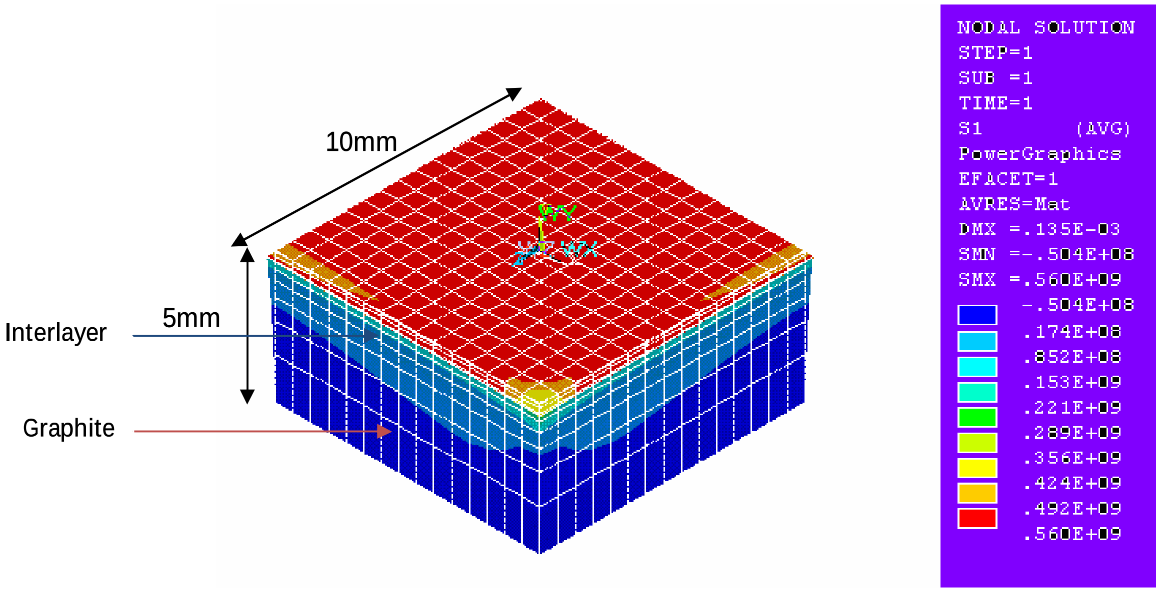

Fig. (4) : Three dimensions principal stress distribution across the diffusion bonding joint using 0.1 mm steel interlayer thickness.

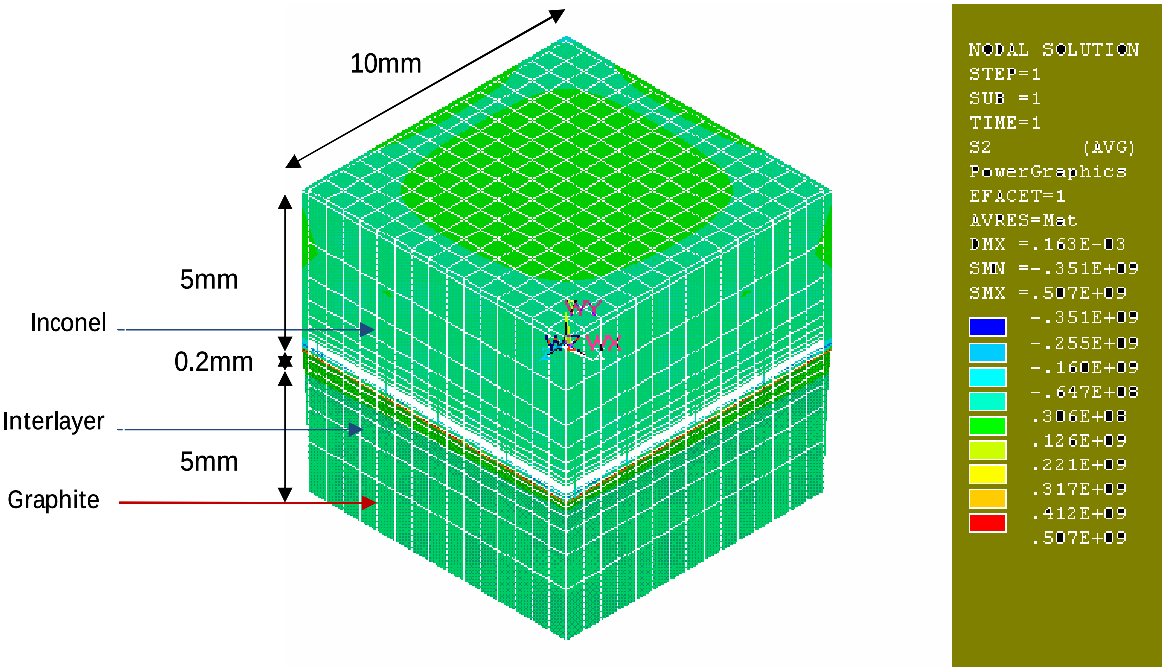

Fig. (5) : Three dimensions principal stress distribution across the diffusion bonding joint using 0.2 mm steel interlayer thickness.

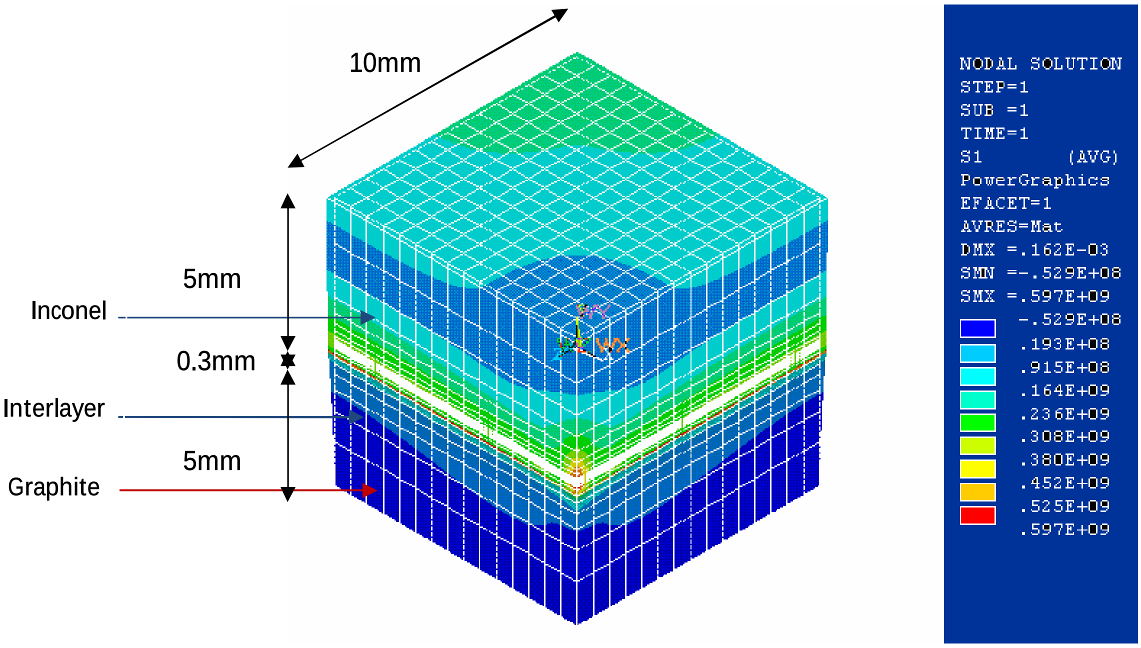

Fig. (6) : Three dimensions principal stress distribution across the diffusion bonding joint using 0.3 mm steel interlayer thickness.

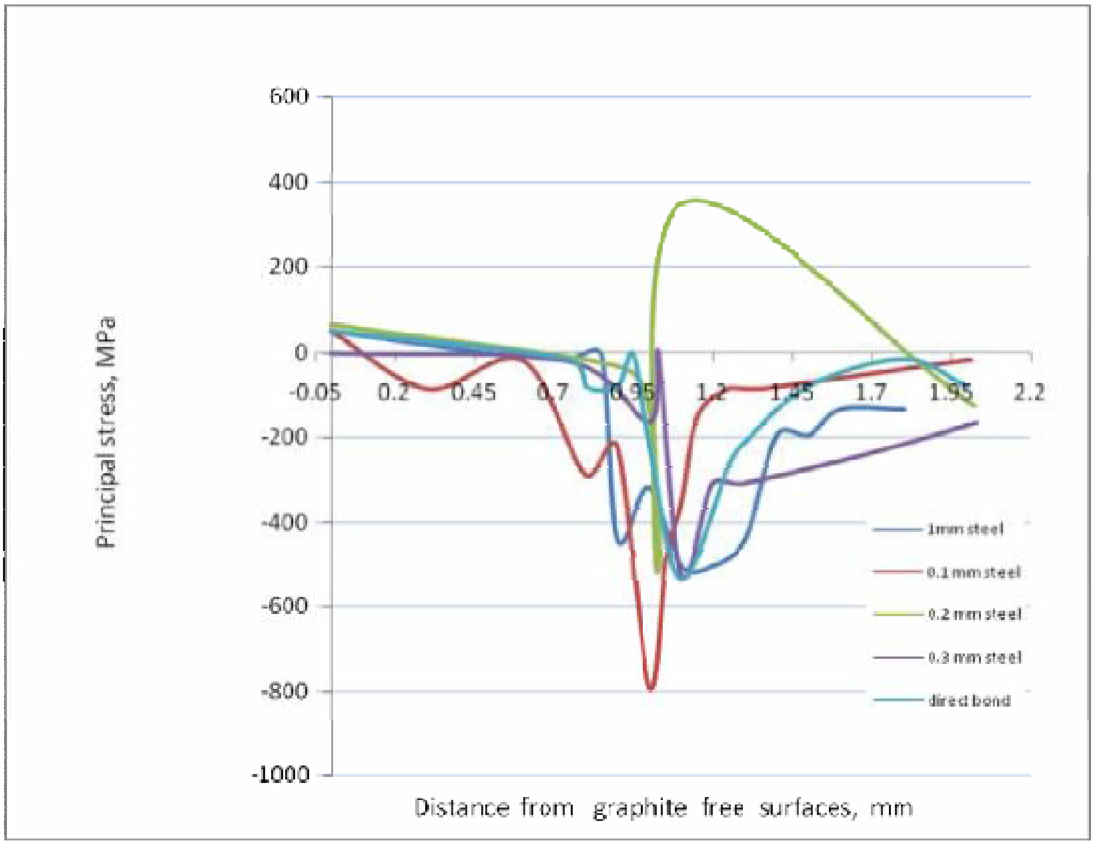

Fig. (7) : Thermal stress distribution on the surface of graphite/ Inconel 600 joint at 800°C diffusion bonding temperature using different steel interlayer thickness. The y-axis represents longitudinal stress as calculated using finite element method.

References

[1] S. Rawal, Metal Matrix Composites for Space Applications, Vol.4, No.53, 2001, pp.14-17. http://www.tms.org/pubs/journals/JOM/jom.html.

[2] D. D. Chung, "Applied Materials Science" CRC Press, Washington D. C, 2001.

[3] A. Abdul-Rahman " Joining Sialon – Stainless Steel and Sialon-Sialon", Ph.D. Thesis, University of Strethclyde, Faculty of Engineering, Dept. of Metallurgy, Engineering Material, 1993.

[4] Elssner G.,"bond strength of Ceramic/ Ceramic joints", first edition Joining of Ceramics, by M.G. Nicholas, 1990, pp.128.

[5] G. M. Mousa "Preparation of Pyrolytic Graphite and Studies of its Physical Properties", Ph. D. Thesis, University of Technology, Department of Applied Science, Baghdad, Iraq, 2002.

[6] Special Metal Corporation, 2004. Internet. www.grantadesign.com/MILpdfs/MIL5-H/MIL5H- AppC.pdf

[7] H. I. Salah "Evaluation of Graphite/ Graphite Brazing", M.Sc. Thesis, University of Technology, Dept. of Production Engineering and Metallurgy, Baghdad, Iraq, 2005.

[8] A. H. Haleem, " Improvement of Inconel 600 Oxidation Resistance by Aluminizing–Chromizing", Ph. D. Thesis, University of Technology, Department of Production Eng. and Metallurgy, Baghdad, Iraq, 2006.

[9] E. R. Wallach and A. Hill, "Modeling of Diffusion Bonding, in Diffusing Bonding (ed. R. Pearce), Cranfield, UK, 1987.

[10] H. P. Kirchner, J. C. Conway & A. E. "Effect of joint Thickness and Residual Stresses on the Properties of Ceramic Adhesive Joint, Theoretical investigation" J. Am. Ceram. Soc., Vol. 70, No.2, 1987, pp. 104-109.

[11] W. A. Zdaniewski, J. C. Conway & H. P. Kirchner, "Effect of joint Thickness and Residual Stresses on the Properties of Ceramic Adhesive Joint, Experimental investigation" J. Am. Ceram. Soc., Vol.70, No.2, 1987, pp. 110-112.

[12] D. J. Stephenson "Diffusion Bonding 2", Elsevier Applied Science, UK, 1990.

[13] Handbook of Applied Engineering Science, 2nd Ed., The chemical Rubber Co., CRC Press, 2001. Internet. www.crystalgraphite.com/graphite/graphiteproperties_A.html

[14] A. Levy, Thermal Residual Stresses in Ceramic to – Metal Brazed Joints, J. Ceram. Soc, Vol. 72, No. 9, 1991, pp. 2141- 2147.

[15] Handbook of Materials Selections, ED Myer Kutz, Pub. John Wiley & Sons, Inc, USA, 2002.

[16]http://www.mineralstech.com/graphite.html1.

[17] S. H. Avner, Introduction to Physical Metallurgy, 2nd ED, McGraw Hill, 1983.

[18] Y. Bienveuu, T. Massart, et al, The Metallurgy of Diffusion Bonding, Cranfield, Ed. Pearce, 1987.

[19] J. P. Holman, Heat Transfer, 4th Ed., Mc Graw-Hill, 1976.

[20] T. Nishada & H. Sueyoshi," Solid State Bonding of Graphite to Inconel 718", J. Japan Ins. Metals, Vol.65, No.4, 2001, pp. 303-309.

[21] T. Nishada and H. Sueyoshi, ," Solid State Bonding of Graphite to Nickel", J. Japan Ins. Metals, Vol.64, No.8, 2000, pp. 597- 603.

[22] T. Nishada and H. Sueyoshi," Solid State Bonding of Graphite to S45C Steel", J. Japan Ins. Metals Vol.63, No.9, 1999, pp. 1212-1217.

[23] H. Sueyoshe, N. Fukuda T. Nishada," Solid State Bonding of Graphite to SUS304 Steel", Mat., Trans., Vol.39, No.10, 1998, pp.1084-1092.

الخلاصة

يَتضمن البحث دِراسة اللِحام الانتشاري (Diffusion Bonding) لإنّكونِلْ 600 مع الكّرافْيتْ الحَرَاري وكذلك باستخدام طَبقة بَينيَة من الفولاذ بينهما بأسلوب المحاكاة، المحاكاة تتَضَمنُ الأنتِفاع مِنْ تَحليلات بَرنامج حَاسوبي (ANSYS) يَعْتَمِدُ تَحليلاً حرارياً ضِمن حُدودِ المُرونَة (Thermoelastic) بإعتماد نموذجا لحِساب الإجهادات الحَرارية المُتكونة عِبرَ الوَصلة المَلحومة لِحاماً أنتِشارياً. إِنَ دراسة مُستويات الإجهادات الحَرَارية المُختَلِفة لها فَائِدة قصوى؛ حيث أن هذه الإجهادات هيَ القُوة الدافِعة لِحُصول الفَشل لِوصلات اللِحام عُموماً. يَتَضَمَن تَحليل اِلعَناصِر المُحَددة (Finite elements analysis)؛ تَسليط الحرارة على جميع الوَصْلة المُرادْ لِحامها وهو المؤثِر الأَساسي لِحُصول اِللحام الأنتشاري، والمؤثر الثاني هو أستخدام طبقات بينية من الفولاذ بسمك مختلف.