CERAMIC MATERIALS: PROCESSING, JOINING AND APPLICATIONS

[1]Tanveer Majeed, [2]Mohd Atif Wahid[#], [3]Nidhi Sharma

[1]M.Tech Student, [2, 3] Research Scholars
[1, 2, 3] Department of Mechanical Engineering,
[1, 2, 3] Jamia Millia Islamia (A Central University),
New Delhi-25, India

[#]Corresponding author details: Mohd Atif Wahid,wahidatif89@gmail.com

Abstract: Ceramics form an important part of material groups. The growth of appropriate joining methods to self-bond hard ceramics or for bonding ceramic to metals has been a major target, aiming at cutting edge applications of ceramics such as engine components and advanced gas turbines. When bonding ceramics, the main difficulty is to get an intimate contact between the materials to be joined and when joining dissimilar materials and specially ceramics to metals, the main concern is the development of high residual stresses in the considered materials. Today a range of joining methods has been developed for joining ceramic to ceramic or ceramic to metal. In this paper processing, joining methods and application of ceramic materials in various fields are discussed.

***Index Terms*-Ceramic, Joining methods, Welding, Applications**, **Thermal expansion coefficients**

I.INTRODUCTION

Ceramic are compounds of metallic and non-metallic elements often crystalline oxide (alumina, zirconia etc.), nitride (cubic boron nitride etc.) or carbide (titanium, tungsten etc.) material. The word ceramic is derived from Greek word *keramikos* which means 'burnt stuff'. In fact the characteristic properties of ceramics are optimized through heat treatments. They have physical properties, which are distinct from that of metallic materials. Thus ceramics, metallic materials, and even polymers tend to complement each other in applications (Kingery et al, 1976).The properties of ceramics vary greatly due to differences in bonding, and thus found a wide range of engineering applications. Ceramics melt at very high temperatures and they show brittle nature under tension. Consequently, the conventional melting, casting and thermo-mechanical processing methods are not good enough to process the polycrystalline ceramics. As a result, most ceramic products are made from ceramic powders through powder processing beginning with ceramic powders. Various forming methods such as pressing, blowing, drawing and fiber forming are chiefly in practice to produce glass objects. Thick glass products such as plates and dishes are fabricated by pressing, blowing produces objects such as jars, bottles and light bulbs, while drawing is used to fabricate long objects like tubes, rods, fibers, whiskers etc.

The bonding of ceramic to ceramic or ceramic to metal was main concern before 2010, aiming at cutting edge applications of ceramics such as engine components and advanced gas turbines (Katano et al, 1993). The need for these joints involves adequate mechanical strength and ability to withstand at high temperatures as many of these applications tend to exploit the significant properties at high temperature of ceramics. When bonding ceramics, the first difficulty is to get an intimate contact between the materials to be joined. When joining dissimilar materials and certain ceramics to metals, the main concern is the development of high residual stresses due to unequal thermal expansion coefficients (CTE) of the considered materials. Today a number of methods have been developed for self-bonding of ceramics or ceramic to metal. Ceramic finds a large number of applications, since ceramics possess high strength at elevated temperature, high wear resistance and high melting point. Ceramic to metal joined materials have wide range of applications in electronic and manufacturing industries as well.

II. FABRICATION AND PROCESSING OF CERAMICS

Ceramics melt at higher temperatures and they show brittle behavior under tension. Hence, the conventional casting, melting and thermo-mechanical treatment routes are not good enough to process the polycrystalline ceramics. Processing of ceramics involves various steps that include processing of powder, Forming, Sintering and Finishing.

2.1 Powder Processing

Ceramic powder processing comprises of powder production by grinding/milling, followed by production of green product, which is then fabricated to produce the final product. A powder is a stock of very fine particles. Production of powder means getting it ready for fabricating by crushing, grinding, separating impurities, blending different powders, drying to form soft agglomerates. Powders are chemically treated to separate different phases and compound to achieve requisite pureness. Finer and homogeneous particles are preferred.

2.2 Forming

Various methods such as, tape casting, slip casting, injection molding and extrusion are then used to amend processed powders into a desired shape to form what is called as green ceramic.

2.2.1 Tape Casting

Tape casting also called as doctor blade process. By tape casting thin ceramic tapes are fabricated. In this process slurry containing ceramic particles, solvent, plasticizers, and binders are made to flow under a blade and onto a plastic substrate. The shear thinning slurry spreads below the blade. The tape is then desiccated using clean warm air. Latterly the tape is subjected to binder burnout and sintering operations. The thickness of tape normally varies between 0.1 and 2 mm. Tape casting is used for making commercially important electronic packages.

2.2.2 Slip Casting

Slip casting uses aqueous slurry, also known as slip, of ceramic powder. The aqueous slurry is fed into a mold of Plaster of Paris. As the water from slurry begins to flow out by capillary action, a thick mass builds along the mold wall. When adequate product thickness is built, the remaining slurry is drained out. It is also possible to continue to pour more slurry in to form a solid piece (solid casting).

2.2.3 Injection Molding

This technique of ceramics is similar to that of polymers. Ceramic powder is blinded with a plasticizer, a thermoplastic polymer, and additives. Then the mixture is injected into a die with use of an extruder. The polymer is then burnt off and the remaining of the ceramic shape is sintered at suitable high temperatures. This is generally suitable for producing complex shapes. **Figure 1** shows the injection molding process.

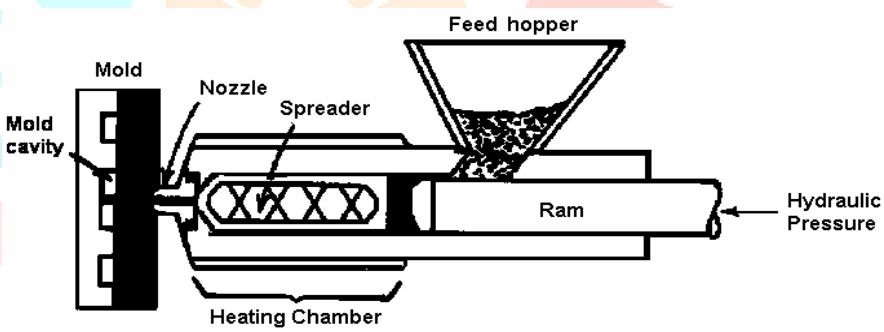

Fig. 1 Schematic diagram of Injection molding

2.3 Sintering

The green ceramic is then strengthened further using a high temperature processes known as sintering or firing. Sintering has the utmost effect on the properties and hence subjected to stringent control. The motivating force for sintering is the reduction in total surface area or surface energy of the powder particles. The major sintering variables are temperature, time and the atmosphere of the furnace. The temperature of sintering is in the range of 75-90% of the melting point of the metal.

2.4 Finishing

For additional enhancement in properties of sintered products and moreover to impart specific features certain additional operations can also be carried out after sintering. These processes include plating, heat treatment, infiltration, coining and sizing etc.

III. JOINING METHODS FOR HARD CERAMICS

An earlier classification of joining methods considered three basic types mechanical joining, direct joining (two straight pieces), and indirect joining (a third interlayer material is interposed between the pieces to be bonded). Another classification considers two basic joining methods, the mechanical and the chemical that encompasses two techniques: those which entail formation of a liquid phase and those occurring in solid state (diffusion bonding, ultrasonic welding, etc.). Other joining methods for ceramics have been the brazing alloy technique and the diffusion bonding; both have been extensively applied to hard engineering ceramics such as Al_2O_3, Si_3O_4, SiC, ZrO_2 etc.

3.1 Mechanical Joining

Mechanical joining comprises methods such as using of bolts, screw threads and shrink-fitting, which takes advantage of the higher CTE of metals that enclose the corresponding ceramic piece on cooling. Mechanical joining also includes Press and shrink fitting which are widely used in mass production.

3.2 Direct Bonding

Direct bonding methods typically use welding and diffusion bonding without using intermediate layers. In welding, the joining temperature must be raised close to the melting point of the pieces and effective results have been limited to few pairs of materials, such as Mo, Nb (Nicholas et al, 1985), mainly due to the stresses induced by CTE mismatch and thermal shock. Some ceramics SiC decompose instead of fusing and consequently cannot be fusion welded. On the other hand, diffusion joining is a solid state temperature activated method driven initially by plastic deformation at the contact asperities and by diffusion and creep in a second stage. The application of load, temperatures in the range of 0.5–0.8 of the absolute melting temperature, and joining times in the range of hours are needed to achieve bonding. The formation of an interfacial reaction zone often takes place as this process involves atomic interdiffusion between both surfaces. Therefore, close contact between the surfaces to be joined entails flat contact and the absence of contaminants and foreign species.

3.2.1 Welding of Ceramics

Several welding methods including fusion welding, brazing, and solid-state welding have been attempted to obtain ceramic-metal dissimilar joints (Uday et al, 2010 and Li et al, 2016). Fusion is used to join metals and glasses and finds wide range of applications in bonding ceramics to metals. In fusion complete contact between surfaces is made, and joints are fabricated for use at temperatures up to the workpiece melting point. However, fusion is limited to a short range of materials. Complete match of complex materials formed in weld pool and balance of melting points and thermal characteristics are important concerns in fusion process. The Various methods of welding of ceramic to metal are:

3.2.1.1 Ultrasonic Welding of Ceramic Materials.

In ultrasonic welding high frequency ultrasonic acoustic vibrations are applied on the materials being joined under pressure to create a solid state weld. In the system, two types of forces are in action, a static normal force applied perpendicular to the interface between the workpieces and an oscillating force generated by oscillation of the contacting sonotrode parallel to the material interface surface. The combined effect of static and oscillating forces produces deformation which promotes welding (Yang and Cao, 2015).Ultrasonic welding can be done in various modes, such as direct welding of ceramics and metals, vacuum deposition of metal coating on ceramic surfaces, and insertion of activated metals between surfaces. While joining metals and ceramics, the welding characteristics are mostly affected by the boundary properties. Previously performed work reveals that there are optimum welding conditions for each metal and ceramic combination and that when welding is performed under such conditions that conform close to these conditions, welding strength and other properties of the joint can be improved to a large extent (SMatsuoka,1994).Major advantage of this welding process is that little heat is generated, virtually no resultant decrease in strength and it can be performed in all environments i.e., either in atmosphere or in vacuum**. Figure 2** below represents the basic ultrasonic welding equipment together with an outline of the joint.

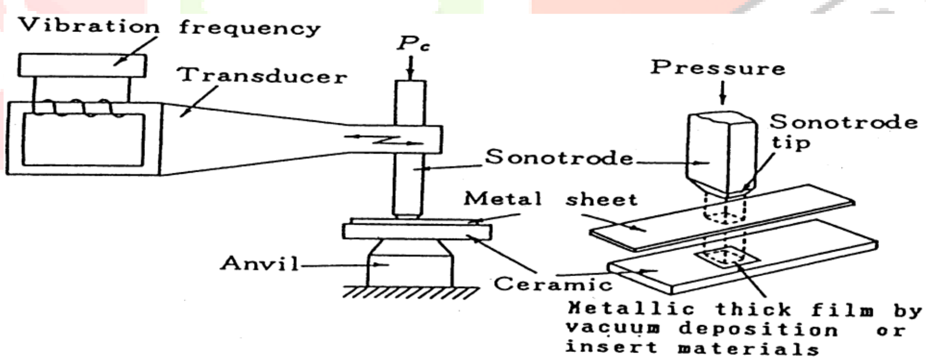

Fig. 2. Basic principle of ultrasonic welding.

3.2.1.2 Friction Welding of Ceramics

Friction welding is a solid state welding process that allows joining of specific material combinations which are considered unweldable by conventional techniques. Among these methods, friction welding has gained great attentions due to its solid-state nature and short welding cycle, which can greatly decrease the thermal mismatch between the parent materials (Li et al, 2016). Sound joint was thus formed. There has been considerable effort towards friction welding of ceramics and metal couples (Uday, 2014, Safarzadeh et al, 2016).The main variables in friction welding are the rotational speed, the axial forces during the friction and forging phases, and the welding time. Friction welding is achieved by rotating and rubbing a metallic specimen against the surface of the ceramic piece, needs. This method is essentially carried out at room temperature but the interface experiences a temperature rise owing to the surface friction. The main hindrances that occur in welding ceramic to metal are difference in the type of atomic bond between a ceramic and metal, different coefficient thermal expansion between materials and brittle and porous nature of ceramics makes it very hard to absorb production defects. **Figure 3** shows the friction welding of alumina to mild steel.

Fig.3 Successful friction welds of alumina to mild steel.

3.2.1.3 Laser Joining of Ceramics in Liquid Phase

The word Laser stands for light amplification by stimulated emission of radiation. Laser Beam Welding (LBW) is a fusion joining process that results coalescence of materials with the heat obtained from intense, coherent, monochromatic beam of light impinging on the joint to be welded. The glass-to-glass welding can be done by employing an ultrashort pulse lasers (Miyamoto 2014, Raju et al, 2016). Because of the ratio of thermal conductivity to thermal expansion of ceramics, a fast and locally restricted energy input by a laser beam will normally generate cracks in the material. Thus the material has to be preheated to decrease the thermal shock effect of laser beam. In order to overcome this disadvantage, preheating is performed by a second laser beam. By welding the ceramic to metals shielding gas such as argon on the upper and lower side are applied to avoid oxidation.

3.3. Indirect bonding

Indirect bonding is the most suitable method of obtaining effective joints using a wide range of intermediate bonding materials. Intermediate materials may be organic adhesives, glass-ceramics, oxide mixtures such as cements and mortars, or metal. The various indirect methods of joining ceramics are briefly described below:

3.3.1 Solid Phase Joining

Solid phase joining is obtained by hot pressing using metallic interlayers. In solid state joining binding agents are not required to wet the ceramic and ductility of metallic interlayers accommodates thermal expansion mismatch between materials more easily. If metals with low melting point are used as interlayers, the joining temperatures can be kept well below at which materials suffer thermal distortion. The mechanisms of joining do not vary much from direct bonding, except that extra provision must be given in mechanical preparation of thin foil interlayers, and care must be given to the effects of interdiffusion between the metal and the interlayers. Adequate interfacial contact initially by plastic deformation and then by creep and diffusion to spheroidize and seal off any residual porosity depends mainly on adequate interfacial contact between materials and interlayer.

3.3.2 Liquid-Phase Joining

Liquid-phase joining processes can be classified according to the type of joining medium such as organic adhesives; metallic brazes and ceramic adhesives. The temperature capability is strongly dependent on the type of interlayer ranging from 200℃ in the case of organic adhesives up to 1200 ℃ for glass–ceramic interlayers. Generally the joining material is either melted or cured in between the surfaces to be joined. After cooling to room temperature, the intermediate layer is detectable as a third body between the joined materials. The advantages of liquid phase joining over the solid-state joining are the ability to completely fill the gap in between the joining surfaces, which makes surface roughness not only dependent, but also the possibility of joining of complex geometries as well. Further, it is a faster process compared to diffusion bonding and its main drawbacks are the lower oxidation resistance and temperature capability.

3.3.3 Indirect Liquid-Phase Joining

Within the joining processes involving filler materials that melt at the joining temperature are the gas–metal eutectic or direct copper bonding (DCB) and TLP bonding. In these liquid-phase bonding processes, a small amount of liquid is formed but it is not detectable at the microscopic level after bonding. Brazing is the most widely used method of joining when joints operating at high temperature are required. Indirect liquid phase joining allows low-cost joining of complicated geometries as it is not limited to flat surfaces. DCB method involves gas reaction with the metal surface to form a eutectic surface composition (Fernie et al, 2009, Greenhut, 2011). The assembly is heated between the melting point of pure metal and eutectic causing the interface to melt. This process is mainly used in the electronics industry, to join Alumina and Aluminum nitride ceramics to copper. The assembly is heated to the joining temperature in presence of Oxygen having partial pressure greater than the equilibrium partial pressure of oxygen over Cu_2O and bond forms through the reaction of Cu_2O with Al_2O_3 to form a few nanometers layer of $CuAlO_2$.

IV. HINDRANCES IN JOINING CERAMIC TO METAL

Since most metals have larger CTE and lower elastic modulus than ceramics, large residual stresses often develop around the interfacial region, which are not totally relieved by cooling from joining temperature. Residual stresses produced play an important role in the mechanical integrity of joints, since they may induce cracking in the ceramic side and plastic deformation in metal side. For common but type symmetrical joints (ceramic–metal–ceramic) and beyond joint-free surface, the stresses along the interface are usually compressive in the ceramic side and tensile in the metal side of the joint (Kirchner et al, 1987), decreasing to zero toward the free edge. On the other hand, stresses perpendicular to the interface are approximately zero everywhere in joined elements except at near surface region of the interface, where compressive stress in the metal and tensile stress in the ceramic develop. In fact, in ceramics maximum tension occurs where stresses are singular i.e., near the free edge of the interface (Kovalev et al, 1998). The developed tensile stress in the ceramic part affects failure characteristics of the joint, often resulting in the fracture of the ceramics at the corners and edges of interfaces. The effects of CTE and yield stress of the metal interlayer on the residual stresses have also been attempted using FEA methods, generally showing that selecting metal interlayers of low yield stress and with CTE closer to the ceramic counterparts was beneficial for reducing thermal stresses. Another important parameter influencing residual stresses is the geometry of the joint. In particular, the elastic stresses in the ceramic side increased for lap joints compared to butt type joints of similar dimensions.

V. APPLICATION OF CERAMICS

Ceramics found a wide variety of applications in various fields. Some of the important applications of ceramics are given below:

1. In the steel-making and aluminum-casting industries, to enhance wear resistance of tubes and blowers used for transferring powders.
2. Ceramic components for automotive parts were developed during the 1980s, like the ceramic turbocharger rotor, combustion chamber or glow plugs, all requiring joining technologies; although most of these developments were successful, they have not come into mass car production (Okada, 2008).
3. Ceramics also find applications as biomedical implants in both dental restoration and femoral prosthesis, where joining is a basic issue.
4. Applications as cutting tools and drilling parts are important for Al_2O_3 and Si_3N_4 ceramics, which also require joining technologies for housing moving structures.
5. High-performance Si_3N_4 materials and SiC composites have been investigated to increase effectiveness and performance of gas turbines for aviation and power generation systems.

VI. CONCLUSION

Ceramics are hard, brittle and have high heat resistance at elevated temperatures. With the advancement of technology various techniques such as direct joining, indirect joining, liquid phase joining provide efficient bonding of ceramics. The development of residual stresses due to difference of CTE of mating materials is a problem of great consideration in joining of ceramics or ceramic to metal. Also proper contact of joined materials is also critical for superior joint strength. However the insertion of metallic interlayers between the ceramics or between ceramic and metal have solved this problem to a great extent. New joining techniques are being continuously developed for proper and efficient joining of ceramics. Ceramics joined materials find a wide range of applications in electronic industry, biomedical, nuclear reactors, etc.

REFERENCES

[1] Kingery, D., Bowen, H. K. and Uhlmann, D. R. 1976.Introduction to Ceramics, Second Edition, Wiley, New York.
[2] Katano, Y., Ando, M., Itoh, T. and Sasaki, M. 1993.Application of ceramics to turbocharger rotors for passenger cars. Journal of Engineering for Gas Turbines and Power transactions of the ASME, 115: 9–16.
[3] Nicholas, M. G. and Mortimer, D. A. 1985.Ceramic metal joining for structural applications. Materials Science and Technology, 1: 657–665.
[4] Uday, M.B., Ahmad Fauzi, M.N., Zuhailawati H. and Ismail, A.B. 2010. Advances in friction welding process: a review, Sci. Technol. Weld. Join. 15: 534–558.
[5] Li, W.Y., Vairis A., Preuss, M and T.J. Ma. 2016. Linear and rotary friction welding review, Int. Mater. Rev. 61: 71–100.
[6].Yang, J. and Cao, B. 2015. Investigation of resistance heat assisted ultrasonic welding of 6061 aluminum alloys to pure copper. Mater Des, 74:19–24.

[7] Matsuoka, S. Trans. J. Soc. 1994. Mater Process. Tech. 47:185.

[8] Li, W.Y., Vairis A, Preuss, M. and Ma, T.J. 2014. Linear and rotary friction welding review, Int. Mater. Rev. 61 (2016) 71–100.

[9] Uday, M.N. and Ahmad-Fauzi, 2014. Joint properties of friction welded 6061 aluminum alloy /YSZ-alumina composite at low rotational speed, Mater. Design, 59: 76–83.

[10] Safarzadeh, M., Noor, A.F.M. and Basheer, U.M. 2016. Effect of friction speed on the properties of friction welded alumina-mullite composite to 6061 aluminum alloy, J. Aust. Ceram. Soc. 52:134–142.

[11] Miyamoto, I. 2013. Laser welding of glass, Handbook of Laser Welding Technologies, pp. 301–331.

[12] Raju, K, Kim, S.,Song., J., Yu,H. and Yoon,D.H. 2016. Joining of metal-ceramic using reactive air brazing for oxygen transport membrane applications, Mater. Des. 109:233–241.

[13] Fernie, J. A., Drew, R. A. L., & Knowles, K. M. 2009.Joining of engineering ceramics. International Materials Reviews, 54: 283–331.

[14] Greenhut, V. A., 2011.Principles and methods of metal-ceramic bonding PM applications. International Journal of Powder Metallurgy, 47: 57–76.

[15] Kirchner, H. P., Conway, J. C., & Segall, A. E. 1987.Effect of joint thickness and residual stresses on the properties of ceramic adhesive joints 1.Finite element analysis of stresses in joints. Journal of the American Ceramic Society, 70:104–109.

[16] Kovalev, S. P., Miranzo, P., & Osendi, M. I. 1998. Finite element simulation of thermal residual stresses in joining ceramics with thin metal interlayers. Journal of the American Ceramic Society, 81:2342–2348.

[17] Okada, A., 2008.Automotive and industrial applications of structural ceramics in Japan. Journal of the European Ceramic Society, 28: 1097–1104.