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Chapter 8

Current Issues and Problems in the Joining of Ceramic to Metal

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Abstract

Ceramics and metals are two of the oldest established classes of technologically useful materials. While metals dominate engineering applications, ceramics have some attractive properties compared to metals, which make them useful for specific applications. The properties of individual ceramics and metals can vary widely; however, the characteristics of most materials in the two classes differ significantly. Joints between a metal and ceramic are becoming increasingly important in the manufacturing of a wide variety of technological product. But joining ceramics to metallic materials often remains an unresolved or unsatisfactorily resolved problem. This chapter deals with problems of various studies in recent years on the joining between two materials.

Keywords: ceramic, metal, joining, problems, reliability

1. Introduction

The successful application of ceramics in many devices and structures requires some type of joining with metal [1]. Therefore, the ceramic-metal joints are used widely in the different applications such as vacuum tubes, high voltage feed through, transistor packages, sapphire-metal windows, rocket igniter’s bodies and many others [2]. The new joining purposes for these materials involve automobile engine components, such as the silicon carbide, silicon nitride and yettria-stabilized zirconia. The ceramic rotor was joined to metal shaft by new method which compensated problems in both shrink fitting and active brazing methods. The designing of ceramic rotor was carried out in order to ensure the strength and durability of the component.
as well as to obtain the same aerodynamic characteristics as in the metal rotor. All applica-
tions have depended upon improved mechanical and thermal properties, such as strength, and
resistance to fatigue, creep and oxidation.

Achieving high integrity joints between ceramics and metals, however, is a challenge. The
properties of ceramics that make them attractive may pose major handicaps for joint fabrica-
tion. Due to the chemical inertness of ceramics, conventional joining methods for metals cannot
be used. To obtain adequate bond quality, high temperature and pressure are often required
[3] and bonding media with reactive elements have been used [4]. The chemical phenomena
occurring at interfaces determine the structure of the interface and hence, its properties. The
chemical reaction between the ceramic and the metal may easily initiate bond formation;
however, thick brittle reaction layers or intermetallics formed at the interface often cause
premature failure at very low stresses [5].

Even successful joint formation does not guarantee mechanical soundness of the joint. The
inherent differences in physical properties between the ceramic and the metal make it very
difficult to find an effective process to join that keeps detailed and comprehensive strength
and flexibility. There are two primary factors that cause the reliability issue of joint such as the
coefficient of thermal expansion (CTE) mismatch and the difference in the nature of the
interface bond. The thermal residual stresses are induced in a joint during cooling due to the
CTE mismatch and differing mechanical responses of ceramic and metal. This may lead to a
detrimental influence on joint strength [5, 6].

The aim of this chapter deals with problems of various studies in recent years on the joining
between two dissimilar materials. The focus is on the general problems, solutions and factors
influencing reliability with different ceramic-metal joining processes.

2. General problems in ceramic-metal joint

There exist many problems between ceramic and metal materials, such as the atom bond
configuration, chemical and physical properties, etc. These problems make the joining of
ceramics to metals difficult. The following main problems such as ionic bonds and covalent
bonds are characteristic atomic bond configurations of ceramic materials. The peripheral
electrons are extremely stable. Using the general joining method of fusion welding to join
ceramics with metals is almost impossible, and the molten metal does not generally wet on
ceramic surfaces [7].

When joining ceramics to metals with the brazing method, for example, metallization on the
ceramic surface is necessary with general inactive brazing filler metal or the use of active
braze alloys in order to get a reliable joint. The thermal expansion coefficients of ceramics
are generally much lower than metals. Stress will be generated in the ceramic/metal joint due
to the thermal expansion mismatch and will degrade the mechanical properties of the joint
and can cause joint cracking immediate after the joining process. The thermal stress in the joint
due to the thermal expansion mismatch should be carefully considered when joining ceramic
with metal. Many ceramics have low thermal conductivity and susceptibility to thermal shock. Using the fusion welding method to join ceramics by concentration heating or with a high energy density heat source, cracking in the ceramic easily occurs. It is necessary to reduce the temperature gradient in and around the fusion zone as much as possible and to carefully control the heating and cooling speed during the joining process.

3. Factors influencing reliability of ceramic-metal joint

Joining ceramics to metallic materials is not so easy to be carried out without considerations of several problems originating from the differences in physical and chemical natures between ceramics and metals to be joined [8, 9]. Figure 1 summarizes the several points, which may cause large scatter in the strength directly. From the microscopic view, interface contact formed by wetting, chemical and physical reaction at interfaces should be of concern in the first place [10]. The cracking in the layer frequently reduces joint strength. Thermal or residual stress in a joint becomes the other important factor. Large thermal stress both in joining process and in services induces flaws into joints. These factors will reflect the distribution of unbonded or weakly bonded is a land like defects on interfaces resulting in substantial reduction in joint strength [11, 12].

Figure 1. Schematics of factors influencing on reliability of ceramic/metal joint [1, 12].

The development of residual stresses is one of the major problems in the ceramic/metal joining at the interface when the material is cooled down from the bonding temperature to room temperature [13]. These residual stresses reduce the strength of the bonded material and in some cases lead to catastrophic failure at or near an interface, during the joining process. The mechanical analysis of a joint metal to ceramic is a very complex problem. There are many different characteristics to look at ceramic/metal joints. Depending on the detailed application, some characteristics are more important than others [14]. Therefore, in the following sections, we will focus in the joining problems researches for factors influencing on reliability of ceramic/metal joint.

3.1. Material reliability

The ceramic, because of its inherent brittleness, is the most critical material for obtaining reliable joints [15]. The base properties of the bulk ceramic member are essential. When the properties of the bulk ceramic are not sufficient, the thermal stress simply fractures the ceramic member. Furthermore, the surface condition of the ceramic is also very important for the joint reliability. The ceramics are produced by the different forming methods and a subsequent densification during sintering at high temperatures. Due to high hardness and brittleness of ceramic, any shaping complicated treatment often needs diamond cutting tools and abrasives. Whereas it should avoid sharp edges and corners that may cause the concentration of tensile stress [16]. Moreover, when the ceramic material is ground by a metal bonded diamond wheel, microcracks are introduced at the surface of the ceramic. The size of the microcracks depends on the diamond grit size of the wheel and also on the rate of material removal. The surface damage can initiate major cracks in the ceramic by the thermal stress and, hence, result in an unreliable joint. Therefore, the ceramic surface should be free of damage to obtain high reliability joints. This condition can be met simply by using sintered ceramic materials. However, nearly all sintered ceramic parts over about 2 cm in size should be grounded, because distortion of the parts during the sintering requires grinding for dimensional control. Ground ceramic materials should be treated further to obtain a defect free surface condition. This can be performed by a resintering or lapping process. In the resintering process, the damaged layer is healed through sintering. In the case of the lapping process, the damaged layer is physically removed. It should be mentioned that the thickness removed by the lapping must completely eliminate the surface damages [15].

3.2. Thermal expansion and residual stress

Residual stresses are stresses that remain in the materials joining after the original cause of the stresses have been removed. Thermal residual stresses play the key role in the mechanical behaviour of various joint materials. Thermal stresses may occur in a heated structure which is rigidly constrained, and also in a structure with temperature gradients. Thermal residual stresses in the ceramic/metal joints can be classified into three groups in accordance with the mechanism that produces them. First, thermal stresses caused by a volumetric change, either expansion or shrinkage, associated with phase transformation. For these stresses arise from a phase change, the temperature must change to cause the phase change. Second, thermal
stresses caused by a difference in CTE mismatch between two materials joined together. For these stresses to arise from a difference in coefficients of thermal expansion, the temperature may be changing or it may have stabilized. Third, thermal stresses caused by a temperature gradient resulting in the thermal differential rates within the volume of the material or within the structure and potentially lead to cracking. For these stresses to arise from differential rates of expansion or contraction, the temperature must change and produce a gradient, which may or may not persist. Whether the temperature gradient persists or not, the thermally induced stresses from this source persist [17].

Ceramic-metal joints represent an important class of components because of their applications in hostile environments. Examples can be found in different application such as automotive, microelectronics, the aerospace industry or biomedical applications. Generally, a ceramic-metal joint develops a residual stress field, which has its origin in the thermomechanical fabrication process and is due to the difference in CTE between the ceramic and metal (Figure 2). Residual stresses have significant effects on the mechanical stability of the interface, since they may cause plastic deformations on the metal side and cracking in the ceramic, thus compromising the adhesion or even inducing failure of the joint.

Figure 2. Comparison of thermal expansion coefficients of metals and ceramics [18].

The residual stresses produced in the ceramic metal joint could be estimated for full elastic conditions according to this equation [7]:

\[ \text{stress} = \frac{1}{E} \times \text{strain} \times \Delta T \]
where $\sigma_C$ is the residual stress after the joint cools to room temperature, $\Delta \alpha$ is the difference of thermal expansion coefficient between materials, $\Delta T$ is the difference between joining temperature and room temperature, $E_m$ is a Young’s model of metal, $E_C$ is a Young’s model of ceramic. If the thermal stresses in the metal exceed its yield strength, the residual stresses in the joint could be determined by [7]:

$$\sigma_C = \sigma_{my} + \Delta \alpha \Delta T E_{mp}$$

where $E_{mp}$ is the linear strain hardening coefficient and $\sigma_{my}$ is the yield strength of the metal (linear elastic-linear plastic conditions are assumed).

The distribution of thermal residual stress is not uniform in the joint and even along the interface between these different materials. The concentration of thermal stress becomes more intense with the proximity of the interface [19]. The most harmful effect of thermal stress is caused by the tensile stress at the interface or in the ceramic. The direction of the maximum tensile stresses is mainly perpendicular to the interface and the free surface direction, causing the crack opening and failure occurs. The breadth of thermal residual stress depends on the shape and dimension of the ceramic/metal interface [20]. For example, the diameter dependence of the thermal stress of the Si$_3$N$_4$/invar alloy joint measured on the surface near the interface as shown in Figure 3. The larger diameter leads to generate more thermal residual stress. It is also noteworthy that stress concentration at the corner of the rectangular bond face joint is more serious. The joint strength tends to decrease with increasing thermal expansion

![Figure 3](image.png)

**Figure 3.** Effect of size and shape of bond face of residual stress on Si$_3$N$_4$/invar alloy joints. The residual stress was vertical to the interface on the Si$_3$N$_4$ surface [22].
mismatch. However, it occasionally happens that some specimen will be strong but the other will be weak even if they are the same kind [20]. This depends on the presence and distribution of internal flaws induced by residual stress during joining. The strengths of the Si₃N₄/invar (iron-nickel alloy) and Si₃N₄/kovar (iron-nickel-cobalt alloy) joints, which are differing in the amplitude of thermal stress, were examined statistically [21].

The thermal stress may be relieved by two different methods according to Lemus-Ruiz’s thesis [23]. One method inserts a metal with approximately the same thermal expansion coefficient as that of the ceramic to decrease the magnitude of thermal stress generated, while the other method involves thermal stress relief by using a ductile metal that easily develops plastic deformation under thermal stress. These two methods may also be employed in combination. Figure 4 shows a schematic illustration of thermal stress at a joint interface and the mode of cracking due to difference of thermal expansion coefficient [24]. When the thermal expansion coefficient, \( \alpha_C \) of the ceramic is smaller than that of the metal, \( \alpha_M \), the ceramic is subjected to tension stress and cracks at the edges, as schematically illustrated in Figure 4a, on the other hand, when the thermal expansion coefficient, \( \alpha_M \), of the metal is smaller than that of the ceramic, \( \alpha_C \); tensile stress acts on the core of the ceramic and cracks the ceramic, not at the edges, but transversely at the core, as shown in Figure 4b.

Figure 4. Schematic illustration of thermal stress in joint interface and mode of cracking due to difference of thermal expansion coefficient [23, 24].

To overcome for reducing the residual stress mentioned above, induced by the mismatch of the thermal expansion coefficient between the materials to be joined, the following methods can be used as reported by Zhou [7]: (1) Using soft filler metals, the soft filler metals have low yield strength and could release the residual stress. (2) Using soft interlayer, the residual stress could be reduced by the elastic and plastic deformation of an interlayer, e.g. when using Al or Cu as interlayer, the residual stress is decreased. According to Eq. (1), the residual stress will decrease with Young’s model \( E_m \) decreasing. (3) Using hard metals of which the thermal...
expansion coefficient is close to ceramics as the interlayer. Using hard metals such as W, Mo or invar as the interlayer, could reduce the residual stress. Their validity is not obvious when hard metals with high yield strength are the interlayer. (4) Using composite interlayer where the composite interlayers often constitute hard metals and soft metals, like Cu/Mo-Cu/Nb, have a noticeable effect on reducing residual stress, with a combination of merits of those two kinds of metals. (5) Joining under low temperature where the joining ceramic to metal at a low temperature is good for reducing the joint deformation and effectively decreasing the residual stresses. (6) Heat treatment after joining because the proper heat treatment post joining sometimes releases the stress and the strength will vary based on the heat treatment. (7) Appropriate configuration of the joint could decrease the stress concentration extent and reduce the residual stress.

3.3. Interface reliability of the joints

Interfaces play critical roles in properties of many material systems such as composites, coatings and joints. Particularly in ceramic to metal joints, the properties of interfaces have a significant effect on the mechanical reliability of the joints. The mechanism of bond formation at the interface determines the interface structure, which depends strongly on processing conditions as well as materials. The bonding mechanisms can be categorized in terms of mass transfer across the interface. When there is only charge transfer without mass transfer across the interface, the bonding is called chemical bonding. In some literature, it is also called physical bonding or adhesive bonding. When there is mass transfer across the interface such as chemical reaction and diffusion, the bonding mechanism is called chemical reaction bonding [5].

3.3.1. Chemical bonding

While atoms are the smallest units for solid-state physicists, interfaces are the smallest building units for material scientists. Heterogeneous interfaces between two different types of materials change the chemical bonding and new properties are formed [25]. Thus, the chemical bonding holds a significant position as a joining technique in this case and includes a chemical bond being created between both parts of the work through utilization of chemical reactions occurring at the ceramic/metal interface. The chemical bonding problem in that joints can be widely produced by chemical bonding at the interface between ceramics (ionic bonding, covalent bonding) and metals (metal bonding), which basically have different bonding modes [26].

The driving force for formation of ceramic-metal interfaces is the decrease in free energy ($\Delta G$) that occurs when intimate contact is established between the ceramic and metal surfaces [27]. The free energy change per unit area of interface formed is given by the Dupré equation [5]:

$$\Delta G = \gamma_M + \gamma_C + \gamma_{MC}$$ (3)
From this article, the diffusion bonding is a technology to achieve compact joint by diffusion of atoms, even chemical reactions between materials or interlayer and materials. The diffusion of atoms in interface is carried out by several mechanisms, such as the replacement of near atoms, movement of clearance atoms and movement of vacancies, etc. The surface of the materials to be joined must be clean and flat (the roughness less than 0.4 μm). Joining time can be a few hours at a mild temperature ($0.6T_m$, $T_m$ is melting point of metal to be joined), also can be several minutes at high temperature ($0.8T_m$). Diffusion bonding can be achieved with inserted interlayer [87–92] or without interlayer [93, 94]. The diffusion interlayer can reduce the cracking, relax the thermal residual stress and improve the joining strength. The diffusion interlayer is produce of different element active to ceramics, such as titanium, niobium and zirconium etc.

Burger and Ruhle [95] studied the material transport mechanisms during the diffusion bonding for niobium (Nb) to alumina ($\text{Al}_2\text{O}_3$). According to this chapter, the many different material transport phenomena may occur during the diffusion bonding process of a metal to a ceramic at high temperatures. The operating transport mechanisms depend on the selected combination of materials as well as on the bonding conditions. So from this work, the results were completed in which different faces in the niobium surface were bonded to a polished alumina surface. The niobium metal had either a very flat polished surface, or well-defined flaws of different shapes and dimensions and that were presented into the surface. The authors were found that the chemical reactions control the transport of materials and according to the conditions chosen for these experiments. As well as the interdependence of the diffusion joining of ceramics and metals requires that two couples have a near contact over the entire area of the joint interface. Even if all defects are detached, there may still be residual thermal stresses due to reaction layers, dislocations, facets, chemical gradients, dislocation arrangements, and precipitates formed during bonding. On Nb/$\text{Al}_2\text{O}_3$ interfaces, thermal stresses are expected to be rather small since the thermal expansion coefficients of both materials are very near. No reaction layer was perceived.

5.3. Ceramic-metal laser welding

Laser welds bonding technique is a new kind of welding technology [96]. It has been developed as an alternative to adhesive bonding and laser welding. Laser welding has a small heat effect zone, which has little effect on the adhesive bonding area [97, 98]. The adhesive in the fusion zone decomposes during the laser welding process, which produces little effect on the properties of the joint. Thus, it can be assumed that laser welding and adhesive bonding hardly affect each other (Figure 18). The advantages of laser welding and adhesive bonding are both included in the laser weld bonding technique. The adhesive provides excellent stress distribution over large bonding areas and laser welding improves the peel resistance of adhesives. Thus, a laser weld bonding joint has better mechanical properties than either a laser welded or adhesive bonded joint alone. Laser welds bonding is a new hybrid technique that combines metallurgical joining, mechanical joining and chemical bonding [96].
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From this article, the diffusion bonding is a technology to achieve compact joint by diffusion of atoms, even chemical reactions between materials or interlayer and materials. The diffusion of atoms in interface is carried out by several mechanisms, such as the replacement of near atoms, movement of clearance atoms and movement of vacancies, etc. The surface of the materials to be joined must be clean and flat (the roughness less than 0.4 μm). Joining time can be a few hours at a mild temperature \((0.6T_m, T_m \text{ is melting point of metal to be joined})\), also can be several minutes at high temperature \((0.8T_m )\). Diffusion bonding can be achieved with inserted interlayer [87–92] or without interlayer [93, 94]. The diffusion interlayer can reduce the cracking, relax the thermal residual stress and improve the joining strength. The diffusion interlayer is produce of different element active to ceramics, such as titanium, niobium and zirconium etc. Burger and Ruhle [95] studied the material transport mechanisms during the diffusion bonding for niobium (Nb) to alumina (Al₂O₃). According to this chapter, the many different material transport phenomena may occur during the diffusion bonding process of a metal to a ceramic at high temperatures. The operating transport mechanisms depend on the selected combination of materials as well as on the bonding conditions. So from this work, the results were completed in which different faces in the niobium surface were bonded to a polished alumina surface. The niobium metal had either a very flat polished surface, or well-defined flaws of different shapes and dimensions and that were presented into the surface. The authors were found that the chemical reactions control the transport of materials and according to the conditions chosen for these experiments. As well as the interdependence of the diffusion joining of ceramics and metals requires that two couples have a near contact over the entire area of the joint interface. Even if all defects are detached, there may still be residual thermal stresses due to reaction layers, dislocations, facets, chemical gradients, dislocation arrangements, and precipitates formed during bonding. On Nb/Al₂O₃ interfaces, thermal stresses are expected to be rather small since the thermal expansion coefficients of both materials are very near. No reaction layer was perceived.

5.3. Ceramic-metal laser welding

Laser welds bonding technique is a new kind of welding technology [96]. It has been developed as an alternative to adhesive bonding and laser welding. Laser welding has a small heat effect zone, which has little effect on the adhesive bonding area [97, 98]. The adhesive in the fusion zone decomposes during the laser welding process, which produces little effect on the properties of the joint. Thus, it can be assumed that laser welding and adhesive bonding hardly affect each other (Figure 18). The advantages of laser welding and adhesive bonding are both included in the laser weld bonding technique. The adhesive provides excellent stress distribution over large bonding areas and laser welding improves the peel resistance of adhesives. Thus, a laser weld bonding joint has better mechanical properties than either a laser welded or adhesive bonded joint alone. Laser welds bonding is a new hybrid technique that combines metallurgical joining, mechanical joining and chemical bonding [96].
The development of more effective joining techniques for structural ceramics could also have a great impact on their use in mass-produced components. However, there are several challenges on component manufacturing by ceramic processing techniques and by the material themselves. Deformation densified ceramics to form complex shapes is practically impossible because most ceramic materials are brittle even at elevated temperatures. Moreover, ceramics are undesirable for mass production because of their high cost and machining difficulties. Effective ceramic joining techniques can play an important role in improving the reliability of ceramic structures as well [100]. Ceramics are very sensitive to flaws, due to the quality of raw materials used in their production and to the characteristics of various processing techniques, such as machining. Several techniques have been developed to join ceramics for structural application: brazing with filler metals; diffusion bonding; microwave joining; and the use of interface layers designed to form a thin transient liquid phase at a relatively low bonding temperature [97].

Many studies have been previously conducted on laser interactions with various metals and semiconductors, but few have been done in the processing of ceramics with lasers [101]. The advanced ceramic composite technology has offered more opportunity to fabricate complex structures of composite ceramic lasers, due to the availability of perfect inherent interface characteristics. One of the main problems in fusion welding of ceramics is to control cracking because of the residual thermal stresses. The result has been to give extra heating in a more extensive region around the zone of weld so that the net thermal slope of the extra heating and the joining source is presently adequately low so that no residual thermal stresses sufficiently high to cause cracking when reached [102]. This extra heating also allows the part to be heated and cooled very slowly enough to avoid thermal shock. In order to avoid weld cracking, and heated ceramic samples with radiant energy formed by halogen lamps, which have been collected by the indicators [103].

Exner and Nagel [104] have investigated about the laser welding of functional and constructional ceramics for microelectronics. They presented successful method of a laser welding process [99].
technology developed in the Laser Institute of Mittelsachsen (Germany). The investigations of alumina laser welding with a purity of 97% showed that in general the technology is suitable. Furthermore, it enables them to carry out the procedure without furnaces and in a natural atmosphere within only a few minutes. It was established, that the high quality of laser welding joints are achievable. Homogeneous structure and lead to no loss of power also, loss of tangible property is not known. The technology permits joining up to a thickness of 3.5 mm. Through using particular preheating it is conceivable to settle the material by metals. The shortest distance from the joining area is more than 25 mm. Implementation of the technology develops the application of ceramic dramatically. All the outstanding advantages of the laser material processing are useful: touchlessness, flexibility, precision and high velocity [104].

6. Conclusion

Advanced ceramics are key materials and are widely used in the electronics, fuel cell, sensor, insulator and Bioengineering fields. The joining of ceramics to metal is necessary and unavoidable in the miniature manufacturing field. Ceramic-metal joining processes and their resulting interfaces have been extensively studied over the years. New developments in the field have granted structural ceramics new horizons in applications involving adverse conditions and reliable materials. However, there still remain several unknown problems. Further experimental evidences could allow a more detailed understanding of the joining mechanism. A small size component (up to approximately 15 mm in diameter) can be joined by using a soft metal or a laminated interlayer for limited kinds of ceramics. How to join large size one with a metal is, however, still one of serious problems because the size dependence of residual stress is so severe. Since most of structural components will be used at elevated temperatures, the examinations on high temperature properties such as strength, oxidation, thermal expansion and thermal stress are required.

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