Jurnal Kejuruteraan SI 1(6) 2018: 23-31
http://dx.doi.org/10.17576/jkukm-2018-si1(6)-04

Two Component Materials in Powder Metallurgy: A Review Paper Focused on the Processing Technique Applied in Powder Metallurgy

(Dua Komponen Bahan di dalam Metalurgi Serbuk: Kertas Kajian Tumpuan kepada Teknik Pemprosesan yang Digunakan dalam Metalurgi Serbuk)

Najlaa Nazihah Mas'ood*, Farhana Mohd Foudzi[a], Abu Bakar Sulong[a,b], Norhamidi Muhamad[a,b], Intan Fadhlina Mohamed[a,b]
[a]*Programme for Mechanical Engineering,*
[b]*Centre for Engineering Materials and Smart Manufacturing (MERCU),*
Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, Bangi, Malaysia

Farrahshaida Mohd Salleh[c]
[c]*Faculty of Engineering, University Teknologi Mara (UiTM), Malaysia*

Ukwueze Bonaventure Emeka[d]
[d]*Institute of Management and Technology, Nigeria*

ABSTRACT

Processing two materials which have different properties gives significant impact to the industries due to their amazing properties which leads in improving the functionality and reliability of products. Many materials have been investigated in terms of layering, bi-material and also co-injection molding process. The two materials may be metal-metal, ceramic-ceramic and metal-ceramic depending on the capabilities requirement. Several techniques have been discussed in this paper regarding improving the hardness properties, magnetic/nonmagnetic and many more. This paper focused on reviewing the methods that were implemented by researchers based on the bonding techniques of two materials. However, both combination metal-metal and metal-ceramic are the most challenging due to their different properties in terms of thermal expansion. For example, in order to control the coefficient thermal expansion (CTE) for each material, before implementing the required process, dilatometer studies are needed. Such study provides an overview on how to suit the diffusion mechanism between the two materials. The benefits and drawbacks for each method were discussed. According to previous researches, the joining of materials such as M2/17-4PH and 17-4PH/zirconia via co-injection molding process have been successful. Such finding is important to evaluate how good the bonding between the two materials is based on the morphology observation at the interface.

Keywords: Two component injection molding; two component material; layering; bi-material; powder metallurgy

ABSTRAK

Pemprosesan dua bahan mempunyai ciri-ciri yang berbeza telah memberi impak besar kepada industri kerana sifatnya yang luar biasa di mana membawa kepada peningkatan fungsian dan kebolehpercayaan produk. Banyak bahan telah dikaji dari segi lapisan, dwi-bahan dan juga proses pengacuan suntikan bersama. Kedua-dua bahan itu mungkin logam-logam, seramik-seramik dan seramik-logam bergantung pada keperluan keupayaan. Beberapa teknik telah dibincangkan dalam makalah ini mengenai peningkatan sifat kekerasan, magnet / non magnetik dan banyak lagi. Kajian ini memberi tumpuan dalam mengkaji kaedah yang telah dilaksanakan oleh penyelidik berdasarkan teknik ikatan dua bahan. Walau bagaimanapun, kedua-dua gabungan logam-logam dan seramik logam adalah yang paling mencabar kerana sifatnya yang berlainan dari segi pengembangan terma. Sebagai contoh, untuk mengawal pengembangan haba pekali (CTE) bagi setiap bahan, sebelum melaksanakan proses yang diperlukan, kajian dilatometer diperlukan. Kajian sedemikian memberikan gambaran mengenai cara menyesuaikan mekanisme penyebaran antara kedua-dua bahan tersebut. Manfaat dan kelemahan untuk setiap kaedah dibincangkan. Menurut kajian terdahulu, penyertaan bahan-bahan seperti M2/17-4PH dan 17-4PH/zirconia melalui proses pengacuan suntikan telah berjaya. Penemuan sedemikian adalah penting untuk menilai betapa baiknya ikatan antara kedua-dua bahan tersebut berdasarkan pemerhatian morfologi di antara muka.

Kata kunci: Pengacuan suntikan dwi-serbuk; dua bahan komponen; pelapis; dwi-bahan; metalurgi serbuk

INTRODUCTION

The fabrication of complex-shaped functional materials have become popular and aimed at attaining combined properties for desired applications. The combination of dissimilar materials such as two metals or two ceramics or metal-ceramic in one component leads to development of a higher density and multifunctional components. Such components have been developed for a wide range of applications designed for wear resistance, high toughness, magnetic, nonmagnetic and high hardness. Such combinations of properties yield obvious advantages over use of monolithic materials in terms of economic relevance, miniaturization, complexity and flexibility of performance. For example, the combination of two materials is able to produce a component with a significant gradient in electrical conductivity (Piotter et al. 2010). The combination of two different materials are well documented. It was reported that for M2/316L composite, each side of such composite showed wear and corrosion resistance behavior (Firouzdor & Simchi 2009). The combination of SS316L and SS17-4PH are desired for magnetic and non-magnetic application (Simchi et al. 2006). The stepwise porosity-graded composite structures, Co–Cr–Mo alloy provides strength at the core and a porous layer for the tissue growth (Dourandish et al. 2008). In addition, $W/2Y_2O_3$ has been reported to be a promising composite for the application of plasma facing components in future fusion power plants (Antusch et al. 2014). Overall, past researchers have highlighted that the process of joining two materials can be challenging.

In order to join the materials, processes such as tape casting, compaction and powder injection molding are normally used such as layered ceramics for electronic graded cutting tools or cost effective components (Rajabi et al. 2015). The barriers in fabricating functionally graded components from powder materials are similar in any production methods or material systems. During such fabrication, the most critical stage is sintering where defects such as cracks, delamination and interface porosity tend to occur. The combination of metal-ceramic can be difficult due to the significant differences in thermal and mechanical properties where adequate mechanical integrity is hard to achieve (Dourandish & Simchi 2009). For example, difference in density leads to different heating rate and strain mismatch (Firouzdor et al. 2008) while difference in coefficient thermal expansion (CTE) leads to bonding failure. Such mismatch is usually induced at the interface region (Dourandish & Simchi 2009). Therefore, it is very vital to control the processing parameters in order to reduce the mismatch strains during sintering. Although the processing seems hard, several researchers have successfully combined two materials if the thermal expansion and sintering kinetics of such materials are similar (Moritz & Mannschatz 2010; Wang et al. 2007).

Till now, the manufacturing of fabrication methods in joining two different materials has been in a great interest among researchers, where several methods clearly improved the conventional manufacturing technologies and reduced the cost. Such methods are based on powder metallurgy (PM) technologies such as powder compaction (isostatic and cold isostatic pressing), plasma spraying and powder injection molding (PIM). Other processes such as tape casting and hot pressed have been reported to fabricate bionic structure of ZrB2–SiC/BN (Wei et al. 2011). For the medical implants, plasma spraying has been widely used to coat HA on Ti6Al4V implants. Such approach showed good adhesion between the HA coating and human bones (Chou & Chang, 2003; Khor et al. 2003). However, for high stress application such as aerospace industry, the removal of porosity is very critical to achieve the desired mechanical properties also can be produced by using Hot Isostatic Pressing (HIP) process. (Bocanegra Bernal 2004). Piotter et al. have reported two components of Al_2O_3/TiN electrically conductive part was successfully fabricated by micro injection molding. Such part was characterized for its rheological behavior, density and shrinkage (Powder Injection Moulding 2005). Finally, co-injection process was used to fabricate nanocrystalline zirconia-430L stainless steel and advanced analytical method was employed to investigate the mechanism of interface formation (Dourandish et al. 2011).

The scope of this paper is to discuss various processing methods to join metal and ceramic such as powder compaction, plasma spray, co-injection molding and cold isostatic pressing. In addition, the factors that influence the bonding strength at the interface are also discussed. Such scope addressed the principles of each process and critical issues that were mentioned in published literatures.

BONDING TECHNIQUES

Powder metallurgy (PM) is often used for processing two component layers due to their composition and microstructure variations that can be controlled and shape forming is possible. Such method is also cost effective for processing complex-shaped parts in large quantity without secondary operations like extensive joining processes (Froes et al. 1996). Methods that have been applied to produce two component layers such as metal-metal layers and ceramic-metal layers in PM processing are powder compaction, hot isosatatic pressing, plasma spraying and co-powder injection molding. Through all of these processes, it is divided into two categories which are conventional and non-conventional. Powder compaction is a conventional while non-conventional processes are hot isostatic pressing, plasma spraying and co-powder injection molding.

POWDER COMPACTION

Compaction is step in which blended powders are pressed into various shapes in dies. The powder which is feedstock is fed into the die by a feed shoe and the upper punch descends into the die. However, as reported by Javad et al. (2013), co-compaction process is different process between compaction processes. Two-layered component is produced in co-compaction by rotating a punch in contact with the first layer and then adding the second layer over it as shown in Figure 1.

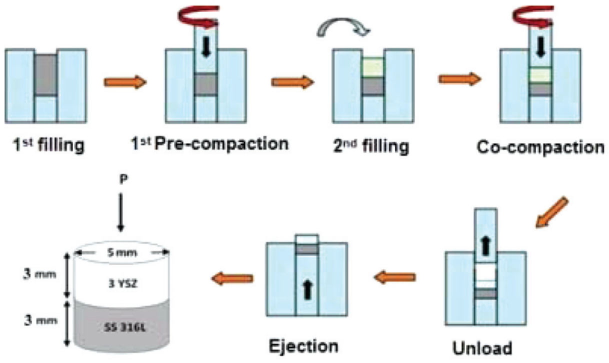

FIGURE 1. Fabrication steps of a bi-material component via powder compaction (Javad et al. 2013)

After implementing the co-compaction process, the process is continued with co-sintering process. It is same with powder injection molding process where the sintering process is needed to produce final product. If sintering process is the process whereby green compacts are heated in a control atm. furnace to a temperature below the melting point of the single material that used for the study, therefore, co-sintering also is same. The different is only two materials is used when producing the green compacts. Hence, both melting temperature must be particular for the co-sintering process. It was reported that sintering process is the most critical stage for eliminating the mismatch stresses that occur at the bonding zone. Such stresses result to the formation of pore bands (Firouzdor & Simchi 2009). However, it is similar when discuss about co-sintering process but in co-sintering was conducted on several metal-metal composite layers such as 17-4PH/316L stainless steel, 728/ 618 Inconel alloys and M2/316L with different particle sizes. Dourandish et al. in have found that the mismatch strain between metal-ceramic composites such as 3Y-TZP/17-4PH, 316L and 420 stainless steel (SS420) during the co-sintering were significant and resulted to failure of bonding joint (Dourandish et al. 2008; Dourandish & Simchi 2009; Dourandish et al. 2011). In order to minimize such issue, pressureless co-sintering method was utilized to diffuse metal-ceramic joint. Such metals and ceramics are stainless steels (17-4PH, 316L and 420) and 3Y-TZP (particle size of 75nm and 150nm) ceramic, respectively. According to Javad et al. they have succeed to produce two-layered component by using co-compaction process. The materials that used in their study are SS316L/nanocrystalline yttria-stablized zirconia (3YSZ). For co-sintering process, they have used vacuum at elevated temperature. The isothermal and non-isothermal sintering of the powders and composite layers were performed in hydrogen, argon and vacuum environment. It was found that the sintering of such zirconia with SS420 under vacuum environment was successful compared to 17-4PH and 316L stainless steels. In addition, fine particle helps in reducing the mismatch shrinkage where particles at 75 nm gives a good bonding mechanism compared to that of 150 nm. During co-sintering, a reaction layer will be formed at the interface region when such layer will accommodate the residual stress that prevents fracture during cooling (Dourandish et al. 2008). For deeper investigation on the diffusion mechanism that takes place during sintering of two different materials, dilatometer analysis was used (Dourandish & Simchi 2009; Dourandish et al. 2011; Firouzdor & Simchi 2009; Firouzdor et al. 2008).

CO-POWDER INJECTION MOLDING

Powder injection molding (PIM) is an advanced manufacturing technology that fabricates metal or ceramic powders into desired shapes or parts at competitive cost (Supati et al. 2000). The early stage of PIM begins with the mixing of metal or ceramic powders with a binder to produce a feedstock. Next, such feedstock will be fabricated and flows into mold cavities to form the desired green part. The green part will be debound and sintered to form the final part (Khakbiz, Simchi & Bagheri 2005). In the past, many researchers have used PIM process for various single materials such as hydroxyapatite (HA), 316L stainless steel, tungsten carbide (WC) and many more. However, due to the increasing demands on fully operational components made of two or more materials that match the needs of desired applications, co-PIM has been introduced to achieve such demands.

Co-PIM has been employed in surface engineering fabrication for several years. Such method employs in two feedstocks that are sequentially injected into a mold to form the surface layer and core of two different materials (Alcock 1999; Heaney et al. 2003; Stephenson & McKeown 2000). Co-PIM can be conducted in two ways. First, a two single-barrel injection molding machine will be used where the first feedstock is injected first into the mold. Next, the injected part is transferred to another single barrel machine where the second feedstock is injected (Baumgartner & Tan 2002). The second technique is the twin-barrel injection molding machine, as shown in Figure 2. The first feedstock is filled into the mold cavity where such mold will be rotated and the second feedstock is injected around or adjacent (Jeffrey et al. 1998; Heaney et al. 2003). The advantage of using a twin barrel is that it does not require the transfer of feedstock since the same mold will be used. Since the second feedstock is injected right after the first feedstock, both feedstock will be cooled together. Such cooling reduces the thermo-mechanical stress caused by the temperature difference (Baumgartner & Tan 2002).

The joining of two materials such as metal-metal and metal-ceramic has become challenging in co-PIM/co-MIM. Alcock et al. have used the co-PIM process to fabricate SS316L/carbonyl iron as a core/shell component (Alcock 1999) while Heaney et al. have investigated the sintering behavior of co-injection molded parts made from tool steel with stainless steel (Heaney et al. 2003).

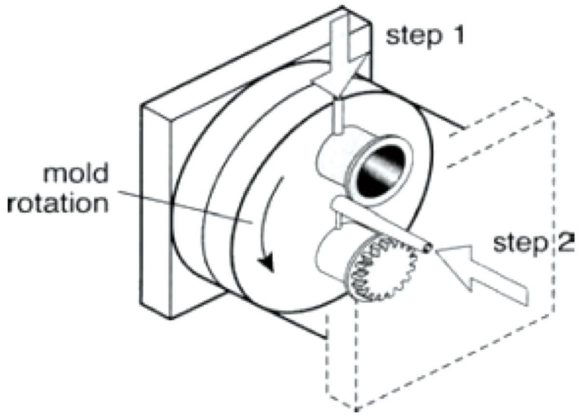

FIGURE 2. Schematic of twin-barrel injection molding (Heaney & Suri 2003)

Co-PIM was utilized for fabrication of micro-sized parts (Imgrund, Rota & Wiegmann 2007; Ruh et al. 2008). In addition, Al_2O_3 and TiN have been combined to develop a U-shape heater element which is a micro two components (Volker Piotter, Finnah, Zeep, Ruprecht & Haußelt 2007). Figure 4 depicted the fabrication of encoder by IFAM where the materials are SS316L (non-magnetic) and SS17-4PH (ferromagnetic) (Ye, Liu & Hong 2008). Several obstacles were formed during the development of fully functional graded components where the two materials must have similar thermal expansion, densification behavior in order to give a good interface bonding characteristic. Therefore, the difference in sintering behavior is the main concern since defects can be easily formed during this stage (Heaney et al. 2003) as shown in Figure 3.

M2/316L-0.5B Fe-10Cr-0.5B/M2 Fe-10Cr-0.5B/316L-0.5B

FIGURE 3. Sample of co-sintered products where only M2/316L-0.5B is successfully produce (Heaney at al. 2003)

Dilatometry study is capable to determine the compatibility of two materials. It is used to predict the densification and expansion that will occur during the sintering stage. Pest et al. (1997) were among the first researchers that used dilatometer in demonstrating the sintering behavior of M4 tool steel and Fe_2Ni. However, the shrinkage was not fully discussed due to small cracks that were formed at the interface region (Pest et al. 1997). A good bonding mechanism is said to be achieved when the shrinkage at the interface region is controllable. Therefore, similar thermal expansion and densification behavior for both materials can be achieved (Baumgartner et al. and Tan, 2002). The conventional metal injection molding (MIM) can also be applied to fabricate the bimetal structures where several parts made of different metals and alloys were fabricated based on the dilatometry study (Simchi et al. 2006). According to Ukuwueze et al. (2017), a good bonding between SS17-4PH/3YSZ was achieved after sintering. This is due to the dilatometry study that was conducted prior implementing the co-PIM process. Such approach is also stated by other researchers where dilatometry study is much needed (Firouzdor & Simchi 2010). Based on the dilatometry study, the binder selection is also important (Ismail et al. 2008). Overall, by using co-PIM, materials having different physical and mechanical properties can be joined together without additional operation.

HOT ISOSTATIC PRESSING

Hot Isostatic Pressing (HIP) is an effective method for the densification of ceramic powder where near net shape ceramic parts having superior properties and performance are possible (Larker & Larker 1991). Such method combines high temperature and isostatic pressure to achieve a high dense component. HIP has always been a great motivator for commercializing components due to its ability in producing complex shapes with tight tolerance that reduces the cost of machining significantly (Zimmerman 1998). During HIP, the material compositions can be optimized in order to obtain a pore-free sintered part. It was reported that HIP not only helps in healing the defects in green bodies but also reduces the external forces such a gravity during sintering. Such reduction of external forces prevents sagging and slumping (Larker 1985). In addition, HIP suitable for brittle materials due to uniform heating and elimination of preferred orientation.

HIP requires pressure medium, usually argon or nitrogen which is pressurized up to 200 MPa where a furnace in the vessel produces a temperature up to 2000^{o}C (Loh & Sia 1992). The part or powder material is encapsulated in a preform or a capsule. The final shape is greatly influences by the HIP structure that consists of time variation of the applied heat and pressure prior reaching their final values (Govindarajan & Aravas 1994). The densification mechanism is due to plastic yield, creep of materials and boundary and also surface diffusion (Ashby 1974; Helle et al. 1985; Swinkels & Ashby 1981).

Unlike isostatic pressing where uniform pressure is applied on all sides of the component, the conventional unidirectional pressing uses mechanical force. Such component is placed in a die and the pressure is applied along a single axis by a ram in unidirectional pressing (Atkinson & Davies 2000). Therefore, the density on the pressed compact varies due to the pressure variation that resulted from the friction that occurred between the walls of the die and the object. Such friction leads to non-uniform grain growth and sintering defects. HIP was originally developed for diffusion bonding of nuclear fuel elements. However, HIP is found to be applicable in other areas such as consolidation of castings, powder metal parts or ceramic parts to full or near theoretical density. In addition, diffusion bonding of similar and dissimilar materials (especially where conventional brazing lacks adequate integrity), densification of high performance castings and rejuvenation of fatigue damaged parts.

HIP has been widely applied due to the optimised mechanical properties of the final part, cost reduction and able to achieve complicated shape. Most stainless steel powders which are conventionally cold compacted or sintered are water atomised (Jeon & Kim 1999). Therefore, powder atomised in inert gas is normally used to prevent oxidation and consolidated by HIP, followed by hot deformation process in order to fabricate the final part (Loh & Sia 1992). Johnson and Heaney (2005) provides more information on the performance of gas and water atomised powders in which sintered components of Co-28Cr-6Mo were isostatically pressed and heated as shown in Figure 4. It was observed that the density for both gas and water atomised powder increased as the temperature increases. The density for gas atomised powder was found to be higher than that of water atomised powder. It was also found that the mechanical properties of Co-28Cr-6Mo exceeded the ASTM F1537 requirements for wrought materials for both water and gas atomised powder. However, presence of oxide inclusions were spotted for the water atomised product.

Therefore, HIP is a good candidate to densifies metal powder where several investigations have been conducted on the densification behaviour of stainless steel 316L powder (Besson & Abouaf 1991; Kim & Jeon 1998). Same metal has also been used by other researchers such as Jeon and Kim (1998) where near net shape forming of an axisymmetric part for an aeronautical turbine.

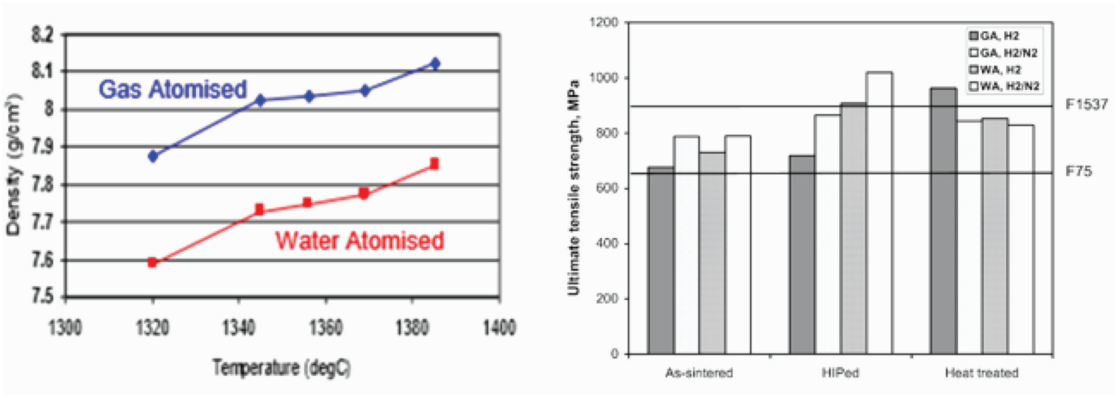

FIGURE 4 (a). Graphs of sintered density and (b) tensile results for Co-28Cr-6Mo made from gas and water atomised powders (Johnson and Heaney 2005)

Based on Figure 4, the presence of pressure during sintering process accelerates the kinetics of densification that results to less time and lower temperature requires for densification. Such result limits the grain growth that improves the packing and gives higher strength. Therefore, greater uniformity of material gives greater densification, flexibility in composition and excellent net shape are possible with HIP. Most processing techniques lead to heterogeneous density within green compact due to frictional forces between the particles (Atkinson & Davies 2000). HIP is well applied on yttria stabilized zirconia (YSZ) and other high performance ceramics. It was well mentioned that full dense nanocrystalline YTZP (45 nm grain size) was achieved using pressureless sintering at 1100^{o}C followed by HIP at 1250^{o}C for 2 hours with glass cladding (Chaim & Hefetz 1998).

Diffusion bonding remains a common application for HIP processing of high performance components since it was originally designed for this purpose. Thin or thick layers of corrosion or wear resistant alloys can be bonded on substrates of metal or ceramic components. High cost materials can be conserved by using them in selected high wear locations (Zimmerman & Jerry 2008). Thus problems of conventional joining and uniaxial diffusion bonding techniques can be eliminated. Zirconia is frequently used as a thermal barrier coating to improve efficiencies of aero engines and gas turbines for power generation (Schulz et al. 2003). As reported by Khor (1997), the modifications in the pore distribution of YSZ using HIP revealed that the density of coating was also increased due to the reduction of average pore size.

HIP is also used to produce HA coating on a Ti substrate in which pressurized gas is applied to exert the requested load at the desired temperature. This requires gas-tight metal or glass encapsulation around the porous HA coated implant (Herø, Wie, Jørgensen & Ruyter 1994).

COLD ISOSTATIC PRESSING

Another variant of Isostatic pressing is the cold isostatic pressing (CIP). In isostatic compaction, a uniform pressure is applied to all external surfaces of the powder body simultaneously (Eksi 2002). However, when the isostatic pressing is performed at room temperature, it is referred as CIP. There are two main processing routes such as wet bag and dry bag isostatic pressing. In both techniques, the powder is sealed in an elastomeric mold, which is then pressurized by a liquid which makes the powder becomes set under (hydrostatic) pressure (Oberacker 2012). Elastomers such as natural and synthetic, silicon rubber, polyurethane and poly vinyl-chloride prove to be good candidates for bag materials.

Characteristic of CIP provides more uniform pressure distribution on the compact compared to density gradients obtained with die pressing. Thus, CIP produces high density and homogeneity of density distribution in compacts and is frequently applied for densification of ceramic powders. For instance, (Maca et al. 2005) reported that zirconia nanoparticles (stabilized by 1.5 and 3 mol. % of yttria) with particle size below 10 nm were prepared using a sol-gel synthesis. It was found that the green bodies had pore radii smaller than 5 nm after CIP. After pressureless sintering at 1100°C, the bodies had a density exceeding 99% of the theoretical density and grain size below 80 nm. Pore size distribution in green bodies was noticed as the most important factor for sintering behaviour of the samples.

Currently, wet bag process is widely used in the production of blanks which are shaped by conventional techniques either in their green or partially sintered states (Oberacker 2012). Recent applications include dental zirconia milling blocks (Höland et al. 2009). Components as filter element, crucibles, tubes, milling or bearing balls, spark plug insulators, small ferrite parts, and of special structural parts with threads or undercut which are not achievable by die compaction are possible with CIP (Oberacker 2012).

PLASMA SPRAYING

Plasma spraying is a process where metallic and non-metallic materials are lodged in a molten or semi-molten states on a prepared substrate (Fauchais 2004). The principal concern when utilizing plasma spraying is to provide a coating to the substrate. The coating-substrate adhesion mechanism appeared in this process is mechanical interlocking. The subsequent solidification which leads to mechanical interlocking occur when irregularities of a rough surface are filled with the spreading molten materials due to the impact pressure (Yılmaz 2009). Coating process has been applied in many manufacturing industries such as aerospace, aircraft, biomedical (Paszkiewicz et al. 2005) and load bearing (Goller et al. 2004). Past research shows that coating can provide wear resistance, corrosion resistance and bio-reactivity for biomedical applications (Yılmaz 2009). For instance, Al-Al_2O_3 coating proved to be as effective as pure Al coating in providing corrosion protection under the exposure of alternate immersion in salt water and salt spray environment.

Alumina coatings are extensively utilized for a variety of industrial applications such as thermal insulation, wear resistance and corrosion protection (Liu et al. 2014). The usefulness of coating broadly applies in biomedical application where hydroxyapatite is coated onto titanium/titanium alloy implants. This method has become cost effective and established for surface modification treatment. However, the coating was found to decreases in thickness and becomes weak due to mismatch in the thermal coefficient of expansion of HA (ceramic) and Titanium (metal) (Cannillo et al. 2008). Guilemany also found in their study on metal-ceramic coating that the interface of metal-ceramic coatings did not form any metallurgical joints. However, there has a research in doing self-fluxing of Ni-17Cr-4.5Fe-4.5B-3.5Si that developed for industrial GTE turbine section components, which, after spray deposition, is fused (densified and solidified) in vacuum at high temperature as shown in Figure 5 (a,b) (Nicoll 1982).

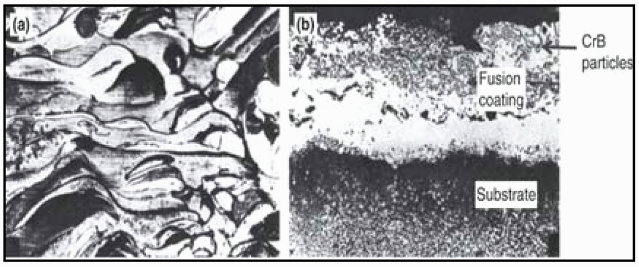

FIGURE 5. Cross-sections of self-fluxing Ni17Cr-4.5Fe-4.5B-3.5Si overlay coating on a Inconel substrate: (a) after initial plasma spraying (b) after vacuum annealing at 1100°C Nicoll 1982)

Consequently, it is challenging to ensure if a good bonding mechanism and strength of metal and ceramic coatings is achieved. The mismatch between the ceramic coating layer and the metal substrate has been investigated due to their differences in chemical and thermal properties (Oktar et al. 2006). The researchers have reported that the brittle nature of ceramic coating produced fractures and cracks and irregularity in densities during cooling of sprayed particles (Scardi et al. 1996; Takeuchi at al. 1990). This is due to the thermal stresses that were generated from the differences in coefficient of thermal expansion (CTE) during the solidifying process (Cannillo et al. 2008) (Muñoz et al. 2006). The residual stress is also formed at the bonding interface of the coating and substrate (Fauchais 2004). In order to overcome such problem, bond coating has been proposed where an intermediate thin layer of a third phase is introduced between coating and substrate (Chou & Chang 2003; Oktar et al. 2006; Zheng et al. 2000). This concept provides better matching of thermal expansion coefficient between ceramic and metal and therefore reduces the residual stresses at the interface of bonding layers. Oktar et al. (2006) have investigated the Al2O3/TiO2 bond coating between Ti-6Al-4V and apatite. It was found that the presence of a third phase that seems to close the gap between the two phases. Such closing leads to no micro cracks and homogeneity of the coating layer is higher. The presence of TiO2 probably assisted the matching of the metallic nature of Ti and the ion covalent ceramic, while Al2O3 provided durability to the joint (Oktar et al. 2006).

The adhesive strength is usually evaluated based on the surface roughness, coating properties, residual stress and mechanical interlocking between the coating and the substrates. The cohesive strength is determined by coating properties such as microstructure and crystallinity (Yang & Chang 2001). The bonding strength of HA coatings on metallic substrates by several techniques such as the standard tensile adhesion test (Gu et al. 2004), interfacial indentation test (Macwan et al. 2015), tensile adhesion strength (Yang & Chang 2001) and indentation method (Takeuchi et al. 1990). Mohammadi et al. (2007) have demonstrated that the tensile adhesion strength test was measured by the standard adhesion test ISO 13779-4, can be used in conjunction with the interface indentation test to predict the effects of different parameters on the adhesion properties of the HA coating by plasma spraying.

CONCLUSION

This paper has reviewed various material processing methods and the metallurgical characteristics for achieving multi-functional and dense components based on the combination of two dissimilar material system. The underlying principles of each process and critical issues raised in the published literatures were discussed. It can be concluded that these processing techniques have reached advanced level in terms of net shaping capability. The barriers for successful fabrication of functionally graded components have been noted to be similar irrespective of the techniques or material systems employed. The challenges associated with obtaining the reliable components were summarily ambitious. Therefore, it can be highlighted that it is important to reduce the mismatch shrinkage and shrinkage rates during the sintering process order to achieve the best composite layers with great mechanical properties. The approach of using dilatometer to determine the co-sintering behavior prior the actual sintering process was proven to be practical. Although other methods were also capable to produce complex parts at large unit, powder shaping through injection molding is more effective where less production time and cost are needed to produce the similar intricate components with tight tolerances. The application of joining materials will definitely increases due to the continuous demands for various applications that require fully dense and reliable parts.

ACKNOWLEDGEMENT

The authors would like to thank the Ministry of Higher Education Malaysia and Universiti Kebangsaan Malaysia for their financial support under the grant TRGS/2/2014/UKM/02/4/1 and DIP/2016/009.

REFERENCES

Alcock, J. 1999. Co-injection promises further growth for MIM. *Metal Powder Report* 54(6): 30-34.

Alcock, J., Logan, P. & Stephenson, D. 1998. Surface engineering by co-injection moulding. *Surface and Coatings Technology* 105(1): 65-71.

Antusch, S., Commin, L., Marcus, M., Piotter, V. & Weingaertner, T. 2014. Two component tungsten powder injection molding–An effective mass production process. *Journal of Nuclear Materials* 447(1): 314-317.

Ashby, M. 1974. A first report on sintering diagrams. *Acta Metallurgica* 22(3): 275-289.

Atkinson, H. & Davies, S. 2000. Fundamental aspects of hot isostatic pressing: an overview. *Metallurgical and Materials Transactions A* 31(12): 2981-3000.

Baumgartner, R. & Tan, K. 2002. MIM'marries' metals. *Metal Powder Report (UK)* 57(3): 38-42.

Besson, J. & Abouaf, M. 1991. Behaviour of cylindrical hip containers. *International Journal of Solids and Structures* 28(6): 691-702.

Lusvarghi, V. & Sola, A. 2008. Production and characterization of plasma-sprayed TiO2–hydroxyapatite functionally graded coatings. *Journal of the European Ceramic Society* 28(11): 2161-2169.

Chaim, R. & Hefetz, M. 1998. Fabrication of dense nanocrystalline ZrO2−3 wt.% Y2O3 by hot-isostatic pressing. *Journal of Materials Research* 13(7): 1875-1880.

Chou, Bang, Y. & Chang, E. 2003. Influence of deposition temperature on mechanical properties of plasma-sprayed hydroxyapatite coating on titanium alloy with ZrO2 intermediate layer. *Journal of Thermal Spray Technology* 12(2): 199-207.

Dourandish, M., Godlinski, D., Simchi, A. & Firouzdor, V. 2008. Sintering of biocompatible P/M Co–Cr–Mo alloy (F-75) for fabrication of porosity-graded composite structures. *Materials Science and Engineering: A* 472(1): 338-346.

Dourandish, M. & Simchi, A. 2009. Study the sintering behavior of nanocrystalline 3Y-TZP/430L stainless-steel composite layers for co-powder injection molding. *Journal of Materials Science* 44(5): 1264-1274.

Dourandish, M., Simchi, A., Hokamoto, K. & Tanaka, S. Phase formation during sintering of nanocrystalline zirconia/stainless steel functionally graded composite layers. *Materials Letters* 65(3): 523-526.

Ekşi, Abdulkadir, & Saritaş, S. 2002. Effects of powder hardness and particle size on the densification of cold isostatically pressed powders. *Turkish Journal of Engineering and Environmental Sciences* 26(5): 377-384.

Fauchais, P. 2004. Understanding plasma spraying. *Journal of Physics D: Applied Physics* 37(9): R86.

Firouzdor, V., & Simchi, A. 2010. Co-sintering of M2/17-4PH powders for fabrication of functional graded composite layers. *Journal of Composite Materials* 44(4): 417-435.

Firouzdor, V., Simchi, A. & Kokabi, H. 2008. An investigation of the densification and microstructural evolution of M2/316L stepwise graded composite during co-sintering. *Journal of Materials Science* 43(1): 55-63.

Govindarajan, R. & Aravas, N. 1994. Deformation processing of metal powders: Part II–Hot isostatic pressing. *International Journal of Mechanical Sciences* 36(4): 359-372.

Gu, Y. W., Khor, K. A., Pan, D. & Cheang, P. 2004. Activity of plasma sprayed yttria stabilized zirconia reinforced hydroxyapatite/Ti–6Al–4V composite coatings in simulated body fluid. *Biomaterials* 25(16): 3177-3185.

Heaney, D., Suri, P. & German, R. 2003. Defect-free sintering of two material powder injection molded components Part I Experimental investigations. *Journal of Materials Science* 38(24): 4869-4874.

Helle, S., Kenneth, E. & Ashby, M. 1985. Hot-isostatic pressing diagrams: new developments. *Acta Metallurgica* 33(12): 2163-2174.

Höland, W., Schweiger, M., Rheinberger, V. & Kappert, H. 2009. Bioceramics and their application for dental restoration. *Advances in Applied Ceramics* 108(6): 373-380.

Imgrund, P., Rota, A. & Wiegmann, M. 2007. Getting better bonding at tiny interfaces. *Metal Powder Report* 62(3): 31-34.

Jeon, C. & Kim, K. 1999. Near-net-shape forming of 316L stainless steel powder under hot isostatic pressing. *International Journal of Mechanical Sciences* 41(7): 815-830.

Johnson, J. & Heaney, D. 2005. Metal injection molding of Co-28Cr-6Mo.

Khor, K. 1997. Hot isostatic pressing modifications of pore size distribution in plasma sprayed coatings. *Material and Manufacturing Process* 12(2): 291-307.

Khor, K., Gu, W., Quek, C. & Cheang, P. 2003. Plasma spraying of functionally graded hydroxyapatite/Ti–6Al–4V coatings. *Surface and Coatings Technology* 168(2): 195-201.

Kim, K. & Jeon, Y. 1998. Densification behavior of 316L stainless steel powder under high temperature. *Materials Science and Engineering: A* 245(1): 64-71.

Larker, H. 1985. Recent advances in hot isostatic pressing processes for high performance ceramics. *Materials Science and Engineering* 71: 329-332.

Larker, H. & Larker, R. 1991. Hot isostatic pressing. *Materials Science and Technology*.

Loh, N. & Sia, K. 1992. An overview of hot isostatic pressing. *Journal of Materials Processing Technology* 30(1): 45-65.

Maca, K., Trunec, M. & Dobsak, P. 2005. Bulk zirconia nanoceramics prepared by cold isostatic pressing and pressureless sintering. *Reviews on Advanced Materials Science* 10(1): 84-88.

Macwan, A., Marr, M., Kesler, O. & Chen, D. 2015. Microstructure, hardness, and fracture toughness of suspension plasma sprayed yttria-stabilized zirconia electrolytes on stainless steel substrates. *Thin Solid Films* 584: 23-28.

Mohammadi, Z., Ziaei-Moayyed, A. & Mesgar, M. 2007. Adhesive and cohesive properties by indentation method of plasma-sprayed hydroxyapatite coatings. *Applied Surface Science* 253(11): 4960-4965.

Moritz, Tassilo, & Mannschatz, A. 2010. 2C ceramics moves into the industrial reality zone. *Metal Powder Report* 65(3): 22-25.

Ismail, M. H., Muhamad, N. & Omar, M. A. 2008. Charaterization of metal injection molding (MIM) feedstcok based on water soluble binder system. *Jurnal Kejuruteraan* 20: 11-18.

Nicoll, A. R. 1982. Self Fluxing coantings for stationary gas turbines. *Thin Solids Films* 95(3): 285-295.

Oberacker, R. 2011. Powder compaction by dry pressing. *Ceramics Science and Technology* 3.

Oktar, F. N., Yetmez, M., Agathopoulos, S., Goerne, L., Goller, G., Ipeker, I. & Ferreira, J. 2006. Bond-coating in plasma-sprayed calcium-phosphate coatings. *Journal of Materials Science: Materials in Medicine* 17(11): 1161-1171.

Piotter, V., Finnah, G., Zeep, B., Ruprecht, R. & Haußelt, J. 2007. Metal and ceramic micro components made by powder injection molding. *Materials Science Forum* 32: 45-53.

Piotter, V., Mueller, T., Plewa, K., Prokop, J., Ruprecht, R. & Haußelt, J. 2010. Manufacturing of complex-shaped ceramic components by micropowder injection molding. *The International Journal of Advanced Manufacturing Technology* 46(1): 131-134.

Rajabi, J., Sulong, A. B., Muhamad, N. & Raza, M. R. 2015. Powder compaction of bimaterials: stainless steel 316L and nanocrystalline yttria stabilised zirconia. *Materials Technology* 30(5): 313-320.

Ruh, A., Dieckmann, A. M., Heldele, R., Piotter, V., Ruprecht, R., Munzinger, C., Fleischer, J. & Haußelt, J. 2008. Production of two-material micro-assemblies by two-component powder injection molding and sinter-joining. *Microsystem Technologies* 14(12): 1805.

Scardi, P., Matteo, L & Luca, B. 1996. Residual stresses in plasma sprayed partially stabilised zirconia TBCs: influence of the deposition temperature. *Thin Solid Films* 278(1): 96-103.

Schulz, U., Christoph, L., Fritscher, K., Manfred, Bilge, B., Lavigne, O., Dorvaux, J. M., Martine, P., Mévrel, R. & Caliez, M. 2003. Some recent trends in research and technology of advanced thermal barrier coatings. *Aerospace Science and technology* 7(1): 73-80.

Simchi, A., Rota, A. & Imgrund, P. 2006. An investigation on the sintering behavior of 316L and 17-4PH stainless steel powders for graded composites. *Materials Science and Engineering: A* 424(1): 282-289.

Stephenson, D. J. & McKeown, P. A. 2000. Development in powder Co-injection moulding. *CIRP Annals-Manufacturing Technology* 49(1): 191-194.

Supati, R.,. Loh, N. H, Khor, K. A. & Tor, S. B. 2000. Mixing and characterization of feedstock for powder injection molding. *Materials Letters* 46(2): 109-114.

Swinkels, F. B. & Ashby, M. F. 1981. A second report on sintering diagrams. *Acta Metallurgica* 29(2): 259-281.

Takeuchi, S., Ito, M. & Takeda, K. 1990. Modelling of residual stress in plasma-sprayed coatings: Effect of substrate temperature. *In Metallurgical Coatings and Thin Films* 426-435.

Ukuwueze, B. E, Sulong, A. B., Muhammad, N. & Salleh, F. M. 2017. Two-component injection molding of bi-material of stainless steel and ytrria stabilized zirconia -green part. *Jurnal Kejuruteraan* 29: 49-55.
Wang, Z., Qian, J., Jiadi, C., Shaorong, W. & Wen, T. 2007. A study of multilayer tape casting method for anode-supported planar type solid oxide fuel cells (SOFCs). *Journal of Alloys and Compounds* 43(1-2): 264-268.
Wei, Chuncheng, Zhang, X., Hu, P., Han, W. & Tian, G. 2011. The fabrication and mechanical properties of bionic laminated ZrB2–SiC/BN ceramic prepared by tape casting and hot pressing. *Scripta Materialia* 65(9): 791-794.
Ye, H., Liu, X. Y. & Hong, H. 2008. Fabrication of metal matrix composites by metal injection molding – A review. *Journal of Materials Processing Technology* 200(3): 12-24.
Yeo, J., Jung, Y. & Choi, S. 1998. Zirconia-stainless steel functionally graded material by tape casting. *Journal of the European Ceramic Society* 18(9): 1281-1285.
Yılmaz, Ş. 2009. An evaluation of plasma-sprayed coatings based on Al2O3 and Al2O3–13 wt.% TiO2 with bond coat on pure titanium substrate. *Ceramics International* 35(5): 2017-2022.
Zheng, X., Huang, M. & Ding, C. 2000. Bond strength of plasma-sprayed hydroxyapatite/Ti composite coatings. *Biomaterials* 21(8): 841-849.
Zimmerman, F. X. 1998. Isostatic pressing offers production advantages. *Ceramic industry* 148(3): 33-37.
Zimmerman, F. X. & Jerry, T. 2008. Hot isostatic pressing: today and tomorrow. *Avure Technologies*.

*Najlaa Nazihah Mas’ood, Farhana Mohd Foudzi,
Abu Bakar Sulong, Norhamidi Muhamad,
Intan Fadhlina Mohamed
Programme for Mechanical Engineering,
Centre for Engineering Materials and Smart Manufacturing (MERCU),
Faculty of Engineering & Built Environment,
Universiti Kebangsaan Malaysia, Bangi, Malaysia

Farrahshaida Mohd Salleh
Faculty of Engineering & Built Environment,
Universiti Teknologi Mara (UiTM), Shah Alam Malaysia

Ukwueze Bonaventure Emeka
Department of Mechanical and Production Engineering,
Institute of Management and Technology,
P.M.B. 01079, Enugu, Nigeria.

*Corresponding author; email: najlaa.elle@gmail.com

Received date: 11st June 2018
Accepted date: 28th August 2018
Online First date: 1st October 2018
Published date: 30th November 2018