A comprehensive review on the ceramics matrix composites for defence applications

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Abstract

There is the rapid increase in the application of ceramic materials in the industry. One area that is currently receiving significant attention from the scientific community is the different types of application of Ceramic Material Composite in the industry as well as in the Defence applications. The motivation to develop CMCs was to overcome the problems associated with the conventional technical ceramics like alumina, silicon carbide, aluminium nitride, silicon nitride or zirconia – they fracture easily under mechanical or thermo-mechanical loads because of cracks initiated by small defects or scratches. The crack resistance is – like in glass – very low. To increase the crack resistance or fracture toughness, particles (so-called mono crystalline whiskers or platelets) were embedded into the matrix. Ceramic Composite armour materials are currently being investigated by researchers to take the advantage of potential for improved performance and reduced by weight. Within the defence industry , advanced ceramics are at the heart of modern armour system due to their comparatively low weight and high performance during ballistic –scale impacts.

Keywords: Ceramic matrix composites (CMCs), Gas turbines, High-temperature, Oxides, Strength.

1.Introduction

Ceramic matrix composites (CMCs) are a subgroup of composite materials as well as a subgroup of ceramics. They consist of ceramic fibres embedded in a ceramic matrix. The matrix and fibres can consist of any ceramic material, whereby carbon and carbon fibres can also be considered a ceramic material. Carbon (C), special silicon carbide (SiC), alumina (Al_2O_3) and mullite (Al_2O_3–SiO_2) fibres are most commonly used for CMCs [1-3]. The various can be possessed by using different techniques to combat the problem of tribo-corrosion at high temperatures [4]. However, the materials like composites and cermets can provide high wear resistance at room temperature applications like WC-Co-Cr and Al_2O_3-TiO_2 and these materials can also be helpful for high temperature applications [5]. There is another class of materials called Nickel based super alloys , which is widely used by the researchers for high temperature applications[6]. The matrix materials are usually the same, that is C, SiC, alumina and mullite. Recently Ultra-high-temperature ceramics (UHTCs) were Investigated as ceramic matrix in a new class of CMC so-called Ultra-high Temperature Ceramic Matrix Composites (UHTCMC) or Ultra-high Temperature Ceramic Composites (UHTCC)[7-12]. The motivation to develop CMCs was to overcome the problems associated with the conventional technical ceramics like alumina, silicon carbide, aluminium nitride, silicon nitride or zirconia – they fracture easily under mechanical or thermo-mechanical loads because of cracks initiated by small defects or scratches. The crack resistance is – like in glass – very low[13-19]. To increase the crack resistance or fracture toughness, particles (so-called mono crystalline whiskers or platelets) were embedded into the matrix. However, the improvement was limited, and the products have found application only in some ceramic cutting tools. So far only the integration of long multi-strand fibres has drastically increased the crack resistance, elongation and thermal shock resistance, and resulted in several new applications. The reinforcements used in ceramic matrix composites (CMC) serve to enhance the fracture toughness of the combined material system while still taking advantage of the inherent high strength and Young's modulus of the ceramic matrix. The most common reinforcement embodiment is a continuous-length ceramic fibre, with an elastic modulus that is typically somewhat higher than the matrix[20-24]. The functional role of this fibre is to increase the CMC stress for progress of micro-cracks through the matrix, thereby increasing the energy expended during crack propagation; and then when thru-thickness cracks begin to form across the CMC at a higher stress (proportional limit stress, PLS), to bridge these cracks without fracturing, thereby providing the CMC with a high ultimate tensile strength (UTS).

2. Manufacturing

Composites (AMC) are reinforced by, Alumina (Al_2O_3) or silicon carbide (SiC) particles (particulate Composites) in amounts 15-70 vol.%, Continuous fibers of alumina, silicon carbide, Graphite (long-fiber reinforced composites), Discontinuous fibers of alumina (short-fiber reinforced composites). Silicon carbide composites are attractive as structural materials in fusion environments because of their low activation, high operating temperature and strength. The physical properties of composites are generally anisotropic. Silicon carbide particles, ranging in size from about 12 to 38 microns, added to the standard aluminum alloys in volumes of 20 to 40 percent. 20% or 30% are more commonly specified to achieve the following advantages with lower density than other alloy alternatives. Cast metal matrix composites has achieve much success and expertise in casting of 20-40% silicon carbide and these alloys to the increased use of these alloys has numerous applications in the field of CMMCs. High Speed automated Precision machinery, Silicon wafer processing equipment, seals, bearings, heat exchangers, hot flow gas liners, robotics, high quality reflective mirrors, high performance bicycle junctions and components, Ball valve parts, fixed and moving turbine components, brake parts, optical and laser equipment, semiconductor manufacturing equipment. CMMCs materials satisfy these needs and requirements. The material is readily melted and cast into complex geometries utilizing our counter gravity casting techniques. Cast Silicon carbide metal matrix composites also can offer a lower cost alternative to high beryllium content alloy applications. Composite Parameters considered for a given matrix/dispersed phase system: Concentration, Size, Shape, Distribution and Orientation.

2.1 Particle Reinforced MMCs

Particles used for reinforcing include ceramics and glasses such as small mineral particles, metal particles such as aluminum, and amorphous materials, including polymers and carbon black. Particles used to increase the modulus of the matrix to decrease the permeability and ductility of the matrix. Particles are also used to produce inexpensive composites. Rein-forcers and matrices will be common, inexpensive materials and are easily processed.

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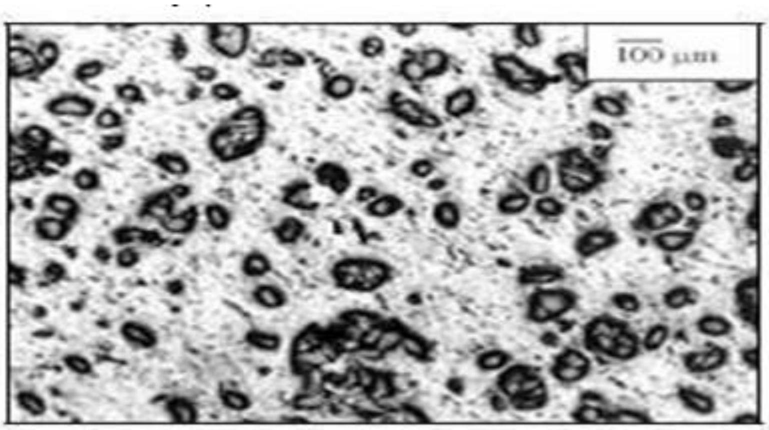

Fig.1. Photo Micro-graphic image of Al-SiC_P

2.2 Short Fiber-reinforced MMCs

MMCs made by dispersing a reinforcing material (SiC) into a metal matrix (Al) as shown in figure 1. The reinforcement surface will be coated to prevent a chemical reaction with the matrix. For example, carbon fibers are commonly used in aluminum matrix to synthesize composites showing low density and high strength. However, carbon reacts with aluminum to generate a brittle and water-soluble compound on the surface of the fiber. To prevent this reaction, the carbon fibers coated with nickel or titanium boride. The matrix is the monolithic material into which the reinforcement embedded, and iscompletely continuous.

Production rates for short-fiber composites (both aligned and randomly oriented) are rapid and intricate shapes formed which are not possible with continuous fiber reinforcement. The reinforcement material embedded into the matrix. The reinforcement does not always serve a purely structural task (reinforcing the compound), but is also used to change physical properties such as wear resistance, friction coefficient, or thermal conductivity. The reinforcement will be either continuous or discontinuous as shown figure 2 (a) and (b).

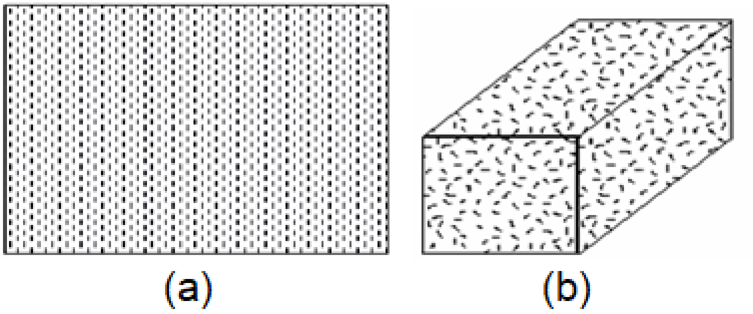

Fig. 2. Short fiber reinforces composite (a) Aligned and (b) Random.

Discontinuous MMCs will be isotropic, and worked with standard metalworking techniques, such as extrusion, forging or rolling. In addition, they machined by using conventional techniques, but commonly would need the use polycrystalline diamond tooling (PCD) [11]. Discontinuous reinforcement uses “whiskers", short fibers, or particles. The most common reinforcing materials in this category are alumina and silicon carbide. Short-fiber reinforced composites consist of a matrix. reinforced by a dispersed phase in form of discontinuous fibers (length < 100*diameter). Applications involving totally multi directional applied stresses normally use discontinuous fibers, which are randomly oriented in the matrix material. Consideration of orientation and fiber length for particular composites depends on the level and nature of the applied stress as well as fabrication cost.

2.3 Long Fiber MMCs

Long-fiber reinforced composites consist of a matrix reinforced by a dispersed phase in form of continuous fibers. Continuous reinforcement uses monofilament are large diameter (about 100-150 µm) wires or fibers such as carbon fiber or silicon carbide. Monofilament are much less flexible than multifilament’s, so they handled as single fiber, rather than bundles, and precautions are necessary to avoid causing damage by imposition of sharp curvature during handling. The fibers embedded into the matrix in a certain direction; the result is an anisotropic structure in which alignment of the material affects its strength. One of the first MMCs used boron filament as reinforcement. The term “multifilament” refers to relatively small diameter (about 5-30 µm diameter) fibers, which are flexible enough handled as tows or bundles.

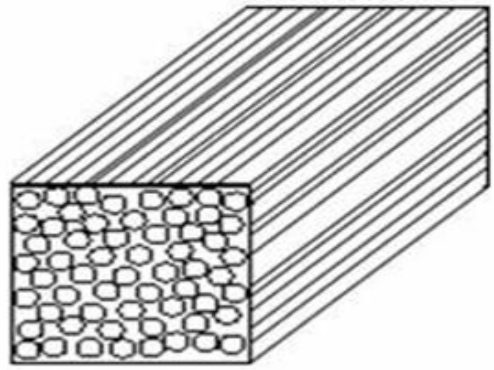

Fig. 3. Long fiber reinforced fiber.

woven, braided, filament wound. The material concerned includes carbon, SiC and various oxides. There has also been interest in carbon fiber reinforced zinc alloys, another system in which interfacial reaction are limited. While SiC has been successful in particulate MMCs, multi-filament SiC fiber suitable for incorporation into metallic matrices are not commercially available. Products on the market, under trade names such as Nicalon, tend to have high levels of free carbon and silica, leading to excessive reaction with most metallic matrices during processing.

2.4 Structural MMCs

The structural composites made up of sandwiches or laminated panels i.e. When a fiber reinforced composite consists of several layers with different fiber orientations, its multilayered (angle-ply) composite in layered form. In structural applications, the matrix is usually a lighter metal such as aluminum, magnesium, or titanium, and provides a compliant support for the reinforcement in high temperature applications, cobalt and cobalt-nickel alloy. The manufacturing processes usually hand lay-up and atmospheric curing or vacuum curing are used. Metallic forms have attracted interest recently – partly because processing advances have led to material becoming available at competitive cost and partly because attractive property combinations obtained, particularly in terms of specific stiffness and specific energy absorption. Several approaches are available to metallic forms. Some of these, particularly those generating closed cell structures, involve processing the metal in the liquid or semisolid state. A problem then arises from the low viscosity of liquid metals. Depending upon the processing methodology employed but this is commonly achieved by introducing dispersion of ceramic into the melt, either as oxide films or as ceramic particles, which raise its viscosity. 3.

Ceramic Matrix composite can be manufactured by several ways. In this section, the various commonly used techniques have been elaborated to have some idea about the on-going research in this field.

2.5 Spray Deposition

Spray casting/deposition is a primary process of composite production whereby the metal sprayed onto a substrate. For composites, the reinforcement is either already incorporated in the sprayed melt (e.g., by stir-casting), combined during spraying with the metal, by injection of the reinforcement ingredient material into the sprayed metal droplet stream, or is co-sprayed, i.e., sprayed at the same time as the matrix onto the substrate. Spray deposition techniques fall into distinct classes, depending whether the droplet stream produced from a molten bath, or by continuous feeding of cold metal into a zone of rapid heat injection. Adaptation to particulate MMC production by injection of ceramic powder into the spray has been extensively explored, although with limited commercial success. Droplet velocities typically average about 20-40 ms^{-1}. A thin layer of liquid, or semi-solid, is normally present on the top of the ingot as it forms. MMC material produced in this way often exhibits inhomogeneous distributions of ceramic particles. Porosity in the as-sprayed state is typically about 5-10%. Thermal spraying is slower, but velocities are higher. Porosity levels are typically at least a few %. Unfortunately, it has very difficult to spray onto fiber arrays to produce MMCs with acceptably low void contents and there are also problem in maintaining uniform fiber distribution.

2.6 Matrix deposition from a gas phase

Chemical vapour deposition (CVD) is well suited for this purpose. In the presence of a fibre preform, CVD takes place in between the fibres and their individual filaments and therefore is called chemical vapour infiltration (CVI)[25-32]. One example is the manufacture of C/C composites: a C-fibre preform is exposed to a mixture of argon and a hydrocarbon gas (methane, propane, etc.) at a pressure of around or below 100 kPa and a temperature above 1000 °C. The gas decomposes depositing carbon on and between the fibres. Another example is the deposition of silicon carbide, which is usually conducted from a mixture of hydrogen and methyl-trichlorosilane (MTS, CH_3SiCl_3; it is also common in silicone production). Under defined condition this gas mixture deposits fine and crystalline silicon carbide on the hot surface within the perform. This CVI procedure leaves a body with a porosity of about 10-15%, as access of reactants to the interior of the perform is increasingly blocked by deposition on the exterior.

2.7 Matrix forming via pyrolysis of C- and Si-containing polymers

Hydrocarbon polymers shrink during pyrolysis, and upon out gassing form carbon with an amorphous, glass-like structure, which by additional heat treatment can be changed to a more graphite-like structure[33-37]. Other special polymers, where some carbon atoms are replaced by silicon atoms, the so-called polycarbosilanes, yield amorphous silicon carbide of more or less stoichiometric composition. A large variety of such SiC-, SiNC-, or SiBNC-producing precursors already exist and more are being developed. To manufacture a CMC material, the fibre preform is infiltrated with the chosen polymer. Subsequent curing and pyrolysis yield a highly porous matrix, which is undesirable for most applications. Further cycles of polymer infiltration and pyrolysis are performed until the final and desired quality is achieved. Usually five to eight cycles are necessary.

2.8 Matrix forming via sintering

This process is used to manufacture oxide fibre/oxide matrix CMC materials. Since most ceramic fibres cannot withstand the normal sintering temperatures of above 1600 °C, special precursor liquids are used to infiltrate the perform of oxide fibres[38-40]. These precursors allow sintering, that is ceramic-forming processes, at temperatures of 1000–1200 °C. They are, for example, based on mixtures of alumina powder with the liquids tetra-ethyl-orthosilicate (as Si donor) and aluminium-butylate (as Al donor), which yield a mullite matrix. Other techniques, such as sol-gel chemistry, are also used. CMCs obtained with this process usually have a high porosity of about 20%. This method is also termed as thin film deposition technique. The schematic diagram for performing this experiment is shown in Fig. 4. The material to be deposited on the base material was ejected from the target in the form of vapour. The atoms sputtered from the target have a high energy distribution and inert gas of closer atomic weight to the target is used for efficient momentum transfer. The types of sputter deposition techniques are Ion-beam sputtering and Ion-assisted deposition. This process has certain disadvantages that it is difficult to control the atoms movement, which further lead to contamination problems. However, this technique can be utilized to produce thinnest layer on the surface of the material. The composite materials can be formed into thin sections by using sputtering technique to enhance the surface properties of the material.

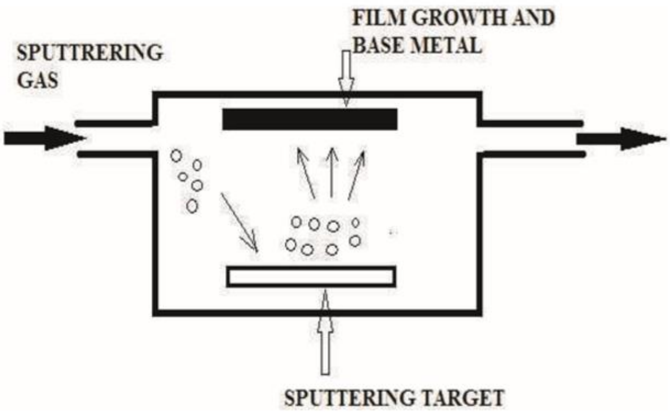

Fig.4.Conventional sputtering process [4]

2.9 Matrix formed via electrophoresis

In the electrophoretic process, electrically charged particles dispersed in a special liquid are transported through an electric field into the preform, which has the opposite electrical charge polarity. This process is under development, and is not yet used industrially.

3. Applications

Heat shield systems for space vehicles, which are needed during the re-entry phase, where high temperatures, thermal shock conditions and heavy vibration loads take place.

- Gas Turbines Components for high-temperature gas turbines such as combustion chambers, stator vanes and turbine blades.
- Components for burners, flame holders, and hot gas ducts, where the use of oxide CMCs has found its way.
- Brake disks brake system components, which experience extreme thermal shock (greater than throwing a glowing part of any material into water).
- Components for slide bearings under heavy loads requiring high corrosion and wear resistance.
- Defence Technology Ceramic armour system were found to be capable of stopping bullets and other projectiles while being more lightweight than other material.
- Ballistic Testing it is generally acknowledged that hardness, Toughness and fracture strength are the key material properties to consider when selecting the Ceramic material .e.g influences the erosion /blunting of the projectile ,and toughness improves the Multi hit capabilities[41-43].

3.1 Developments

3.1.1 Application of oxide CMC in burner and hot gas ducts

Oxygen-containing gas at temperatures above 1000 °C is rather corrosive for metal and silicon carbide components. Such components, which are not exposed to high mechanical stress, can be made of oxide CMCs, which can withstand temperatures up to 1200 °C. The gallery below shows the flame holder of a crisp bread bakery as tested after for 15,000 hours, which subsequently operated for a total of more than 20,000 hours[44].

3.1.2 Developments for gas turbine

The use of CMCs in gas turbines permit higher turbine inlet temperatures, which improves turbine efficiency. Because of the complex shape of stator vanes and turbine blades, the development was first focused on the combustion chamber. In the US, a combustor made of SiC/SiC with a special SiC fibre of enhanced high-temperature stability was successfully tested for 15,000 hours.[28] SiC oxidation was substantially reduced by the use of an oxidation protection coating consisting of several layers of oxides. he engine collaboration between General Electric and Rolls-Royce studied the use of CMC stator vanes in the hot section of the F136 turbofan engine, an engine which failed to beat the Pratt and Whitney F-135 for use in the Joint Strike Fighter. The engine joint venture, CFM International is using CMCs to manufacture the high temperature turbine shrouds. General Electric is using CMCs in combustor liners, nozzles, and the high temperature turbine shroud for its upcoming GE9X engine. CMC parts are also being studied for stationary applications in both the cold and hot sections of the engines, since stresses imposed on rotating parts would require further development effort. Generally, development continues of CMCs for use in turbines to reduce technical issues and cost reduction[45].

3.1.3 Development in Defence

Composite applications in the defence industry include helicopter rotor blades, ballistic protection plates, control surfaces, radomes, doors, and fuselages. The major growth drivers for this market include the increasing use of lightweight and high-performance materials in defence programs, as well as the growing need for lightweight materials in ballistic protection solutions. Emerging trends with a direct impact on the dynamics for composites in the defense industry include the adoption of nanotechnology in ballistic protection materials and a growing focus on stealth technology for military aircrafts. Military aircraft is expected to remain the largest segment, while body armor is expected to witness the highest growth during the forecast period due to growing demand for lightweight and high-strength ballistic protection materials. By reinforcement type, carbon fibre composite is expected to remain the largest segment over the forecast period[46]. Ceramic matrix composites (CMCs) are expected to witness the highest growth due to their high-temperature performance, better wear resistance and good compressive strength[47].

4. Conclusion

From the numerous types of Ceramic composites material, this paper discusses the various application of ceramic composites in the industry and in the defence system. And also discuss its manufacturing methods or fabrications methods to be used in the ceramics matrix composite. CMC has many other application like in marine and ship building fields. The advanced ceramics developed during the last three decades were initially found to have some favourable properties which prompted intensive work for their use as high temperature structural part in process in heat conversion devices .they failed by catastrophic brittle fracture. Although high temperature, resistance to corrosion ,Strength retention , stress rupture and resistance to corrosion is very good.

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REFERENCES

1. T. R. Cooke (1991). "Inorganic fibres- A Literature Review". *Journal of the American Ceramic Society. 74: 2959-2978.*
2. K. Kumagawa; H. Yamaoka; M Shibuysa; T. Ymamura (1998). "Fabrication and mechanical properties of new improved Si-M-C-(O) Tyranno fibre". *Ceramic Engineering and Science Proceedings. 19A: 65-72.*
3. R. Naslain; F. Langlais; R. Fedou (1989). "The CVI-Processing of Ceramic Matrix Composites". *Journal de Phys.Colloque.50:C191-C207.*
4. H. Vasudev, L. Thakur, H. Singh, A review on tribo-corrosion of coatings in glass manufacturing industry and performance of coating techniques against high temperature corrosion and wear, *i-manager's Journal on Material Science. 3 (2017) 38-48.*
5. H. Vasudev, L. Thakur, H. Singh, A. Bansal, Mechanical and microstructural behaviour of wear resistant coatings on cast iron lathe machine beds and slides, *Kovove Materialy , 56 (2018), 1, pp. 55 – 63.*
6. H. Vasudev, L. Thakur, H. Singh, Investigation on microstructural and mechanical properties of HVOF sprayed Inconel-718 coatings on grey cast iron, *Kovove Materialy , 4(2):33-37,2018.*

7. M. Hock; E. Schaffer; W. Doll; G. Kleer. Composite coating materials for the moulding of diffractive and refractive optical components of inorganic glasses, *Surface and Coatings Technology .163 –164 (2003) 689–694.*
8. G. C. Firestone; A. Y. Yi. Precision compression molding of glass microlenses and microlens arrays-an experimental study, *Applied Optics. 2005 ,Vol. 44, No. 29.6115-6122.*
9. Shin_Ichir0 Hirota; Yu oogami; JKaapzauna ki Hashimoto. Method of producing a glass optical element capable ofsuppressing occurrence of a damage of a mold and improving aquality of the glass optical element. *United States Patent,2000, 6,151,915.*
10. Michael K. Budinski, Pittsford; JohnC. Pulver, Spencerport; Jayson J.Nelson, Webster; Eugene G. Hill;David A. Richards, Glass mold material for precision glass molding, *United States Patent,2002, US 6,363,747 B1.*
11. Jiwang Yan; Takashi Oowada; Tianfeng Zhou; Tsunemoto Kuriyagawa. Precision machining of microstructures on electroless-plated NiP surface for molding glass components, *Journal of Materials Processing Technology 209 (2009) 4802–4808.*
12. Allen Y. Yi; Anurag Jain. Compression Molding of Aspherical Glass Lenses–A Combined -Experimental and Numerical Analysis, *Journal of the American Ceramic Society, 88 [3] 579–586 (2005).*
13. Vladimir A. Grodsky. Bronze Glass Molds Replacing Cast Iron Glass Molds, *Journal of the optical society of america, Vol. 40, No. 3 , 1950.*
14. B.I. Yakubovich; K.M. Pogodina-Alekseeva; N.Ya. Ranskeya; L.I.Lopatkina. Thermal fatigue testing og cast iron for glass moulds, Consultants bureau, *A devision of Plenum Publishing corporation ,No.12,9-11,1969.*
15. P.A. Averchenko. The use of heat-resistant silicon cast iron with spheroidal graphite for glass moulds, Consultants bureau, *A devision of Plenum Publishing corporation ,No.11,18-21,1970.*
16. P.A. Averchenko; A.F. Karpenko; A.V. Lisovskil; Yu.S. Puchko; I.P. Kobyako; V.Z. Ostapenko; V.S. Zakharchenko. Using heat resistant silicon cast iron containing spheroid graphite for glass bottle moulds, Consultants bureau, *A devision of Plenum Publishing corporation ,No.7,13,1972.*
17. Jean-Claude Chalon; langy sur Bresle. Cast iron molds for glass making and method of making, *United StatesPatent,1989 ,US 4,830,656.*
18. I.Wadsworth; I.J. Smith;L.A. Donohue; W.-D. Miinz. Thermal stability and oxidation resistance of TiAlNKrN multilayer coatings, *Surface and Coatings Technology, 94-95 (1997) 315-321.*
19. O.B. Kolotilkin; I.P. Volchok; A.A. Kishchenko; I.A. Klyuchink;R.S. Zolotareva; G.V. Zakharov,Improving the service properties of cast iron glass molds, *Consultants bureau, A devision of Plenum Publishing corporation ,No.6,13-14,1985.*
20. H. Seki; K. Satoh;H. Satoh ;K . Matusita ; R. Sato .A new adhesion process of glass to metal using the redox reaction, *Journal of materials science 31(1996)4891-4898.*
21. R.S. Zolotareva ; V.I.Borul;G.S Zakharov. Influence of temperature on the life of the cast iron glass molds ,*Consultants bureau, A devision of Plenum Publishing corporation ,No.6,90-91,1987.*
22. Satoshi Nishiyama ; Eiji Takahashi; Yasuo Iwamot;, Akinori Ebe; Naoto Kuratani; Kiyoshi Ogata. Boron nitride hard coatings by ion beam and vapor deposition, *Thin Solid Films 281-282 (/996) 327-330.*

23. Guenter Kleer ;Walter doell,Ceramic multilayer coatings for glass moulding appliocations, *Surface and Coatings Technology94-95(1997)647-651*.
24. Zoli, L.; Sciti, D. "Efficacy of a ZrB 2 –SiC matrix in protecting C fibres from oxidation in novel UHTCMC materials". *Materials & Design. 113: 207-213.*.
25. Zoli, L.; Vinci, A.; Silvestroni, L.; Sciti, D.; Reece, M.; Grasso, S. "Rapid spark plasma sintering to produce dense UHTCs reinforced with undamaged carbon fibres". *Materials & Design. 130: 1-7*.
26. Galizia, Pietro; Failla, Simone; Zoli, Luca; Sciti, Diletta. "Tough salami-inspired C f /ZrB 2 UHTCMCs produced by electrophoretic deposition". *Journal of the European Ceramic Society. 38 (2): 403-409.*
27. Vinci, Antonio; Zoli, Luca; Sciti, Diletta; Melandri, Cesare; Guicciardi, Stefano. "Understanding the mechanical properties of novel UHTCMCs through random forest and regression tree analysis". *Materials & Design. 145: 97-107*.
28. Lisa Hollands, The Glass to Metal Interface during Container Forming Processes, *Ph.D thesis*, *University of Sheffield,1998.*
29. Michael Cable, Mechanization of Glass Manufacture, *Journal of the American Ceramic Society ,82 [5] 1093–1112 (1999).*
30. Manfred Weck; Markus Winterschladen; Tilo Pfeifer; Dirk Dörner; Ekkard Brinksmeier; Lutz Autschbach; Oltmann Riemer , Manufacturing of Optical Molds using an Integrated Simulation and Measurement Interface, *Proc. of SPIE Vol. 5252*.
31. B.I. Yakubovich; K.M. Pogodina-Alekseeva; N.Ya. Ranskeya; L.I.Lopatkina. Heat resistant cast irons for glass press molds, *Consultants bureau, A devision of Plenum Publishing corporation ,No.2,16-18,1970.*
32. D. Zhong, E. Mateeva, I. Dahan, J.J. Moore, G.G.W. Mustoe, T. Ohno,J. Disamc, S. Thiel. Wettability of NiAl, Ni-Al-N, Ti-B-C, and Ti-B-C-N films by glass at high temperatures, *Surface and Coatings Technology 133-134 (2000) 8-14.*
33. M.I. Lembke, D.B. Lewis, W.-D. Munz. Localised oxidation defects in TiAlN/CrN superlattice structured hard coatings grown by cathodic arc/ unbalanced magnetron deposition on various substrate materials, *Surface and Coatings Technology 125 (2000) 263–268.*
34. J. Brand, R. Gadow, A. Killinger. Application of diamond-like carbon coatings on steel tools in the production of precision glass components, *Surface and Coatings Technology 180 –181 (2004) 213–217.*
35. Chih-Hsiung Lin , Jenq-Gong Duh , Bao-Shun Yau. Processing of chromium tungsten nitride hard coatings for glass molding, *Surface & Coatings Technology 201 (2006) 1316–1322.*
36. K.J. Ma, H.H. Chien, W.H. Chuan, C.L. Chao , K.C. Hwang. Design of Protective Coatings for Glass Lens Molding, *Key Engineering Materials Vols. 364-366 (2008) pp 655-661*.
37. Raymond Viskanta, Jong Mook Lim. Theoretical Investigation of Heat Transfer in Glass Forming, *Journal of the American Ceramic Society, 84 [10] 2296–302 (2001*).
38. Sugwon Kim, S.L. Cockcroft , A.M. Omran, Honam Hwang. Mechanical, wear and heat exposure properties of compacted graphite cast iron at elevated temperatures, *Journal of Alloys and Compounds, 487 (2009) 253–257.*

39. I. O. Leushin ; D. G. Chistyakov. Analysis of Cracking in Glass Molds Made of Cast Iron, *Russian Metallurgy (Metally), Vol. 2014, No. 9, pp. 768–771.*
40. Rudolf stliner,ASM Handbook,Properties and selection of Irons ,*Steels and high performance Alloys .Vol 1,10th edition,1990.*
41. Joel Hemanth, Wear characteristics of austempered chilled ductile iron, *Materials and Design 21 (2000) 139-148.*
42. M. Cingi , F. Arisoy, G. Basman, K. Sesen. The effects of metallurgical structures of different alloyed glass mold cast irons on the mold performance, *Materials Letters 55 (2002) 360–363.*
43. Ali Sarhadi, Jesper Henri Hattel, Hans Nørgaard Hansen. Evaluation of the viscoelastic behaviour and glass/mould interfacefriction coefficient in the wafer based precision glass moulding, *Journal of Materials Processing Technology 214 (2014) 1427–1435*.
44. Yu-Chung Tsai, Chinghua Hung, Jung-Chung Hung. Glass material model for the forming stage of the glass molding process, *journal of materials processing technology 2 0 1 (2 0 0 8) 751–754.*
45. Gregory C. Firestone, Anurag Jain, Allen Y. Yi. Precision laboratory apparatus for high temperature compression molding of glass lenses, *review of scientific instruments 76, 063101 ,2005.*
46. P.H. Mayrhofer_, G. Tischler, C. Mitterer. Microstructure and mechanical/thermal properties of Cr-N coatings deposited by reactive unbalanced magnetron sputtering, *Surface and Coatings Technology 142-144 (2001) 78-84.*
47. P.H.Mayrhofer , F.Kunc , J.Musil , C.Mitter. A comparative study on reactive and non-reactive unbalanced magnetron sputters deposition of TiN coatings, *Thin Solid Films 415 (2002) 151–159.*