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Micro Particles Effect on Mechanical and Thermal Properties of Ceramic Composites - A Review

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***Abstract*—**Particles are the most common and cheapest reinforcement producing discontinuous reinforced composites with isotropic properties. Conventional fabrication methods can be used to produce a wide range of product forms, making them relatively inexpensive. Optimising composite development must include consideration of all the fundamental aspect of particles including their size, shape, volume fraction, distribution and mechanical properties. Research has shown that the challenges of low fracture toughness, poor crack growth resistance and low thermal stability can be overcome by reinforcement with particles. The unique properties exhibited by micro particles reinforced ceramic composites have made them to be highly attractive in a vast array of applications.

***Keywords*—**Ceramic composites, Mechanical properties, Micro-particles, Thermal stability.

I. Introduction

DUE to technological progress, conventional metal alloys, ceramics, and polymeric materials have become insufficient to meet increasing demands on product capabilities and functions [1]. Hence, materials with unusual combinations of properties that cannot be met by the conventional materials are needed. This is especially true for materials that are needed for aerospace, underwater, and transportation applications. For example, aircraft engineers are increasingly searching for materials that have low densities, high strength and toughness (stiffness), high impact and thermal stability, high corrosion and wear resistance [2]. This is a rather formidable combination of properties. Hence, material-property combinations and ranges have been and are being extended by the development of composite materials [3]. Composites are being sought after as replacement for these conventional materials due to the unique properties they exhibit in various applications. Composites represent a definite combination of chemically and structurally different constituent materials whose combination produces a synergistic effect and aggregate properties that are different from those of its constituents [2]. Materials containing fibers or particles reinforcement belong to the class of materials known as composite [4]. A composite can be defined as a combination of two or more distinct materials at a macroscopic level to attain new properties that cannot be achieved by those individual components. Different from metallic alloys, each material keeps its own chemical, physical and mechanical properties [5]. However, the properties of composites are strongly dependent on the characteristics of their constituents in terms of distribution and mode of interaction. This is why composites' behaviours are either the volume fraction sum of constituents' properties or synergy resulting in improved characteristics. Similarly, the concentration and geometry of reinforcements with regard to shape, size and distribution usually imparts significantly on the composite's properties [2].

Compared with traditional metallic materials, the main advantages of composites are: good vibration damping ability, long fatigue life and high wear, creep, corrosion and thermal resistances [5]. The above advantages make composite materials to be widely used in various fields. In aeronautic structures, composite materials are increasingly being utilised to decrease weight for payload and radius purposes. For example, the percentages by weight of composites in USA fighter jets increased from 2% in F-15E to 35.2% in F-35/CV. The overall structure of Euro fighter Typhoon is composed of 40% carbon-fiber composite materials. For commercial aircrafts, the usage percentages of fiber-reinforced composite materials in the latest Boeing B787 and newly designed Airbus A350-XWB reach 50% and 52% respectively. To meet the performance and fuel efficiency requirements, the consumption of composites in automobile industry is growing. The blades of wind turbines are normally made of composites to improve electrical energy efficiency [5]. In ships or infrastructures, composite materials with high corrosion resistance have received wide acceptance. Above all, the brake and engine parts working in high temperature are often fabricated from metal or ceramic composites.

II. Materials Selection in Ceramic Matrix Composites (CMCs)

Some criteria need to be considered before a right selection of reinforcement and matrix materials can be made. Some of these criteria are inter-related and are: compatibility, thermal property, fabrication method, application and cost [6]. The chemical stability, wettability and compatibility of the reinforcement with the matrix material are important, not only for materials fabrication, but also for application because all reinforcements are not compatible with every matrix. The wetting and bonding between the matrix and reinforcement are generally regarded as the major issues in producing composite

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materials [7]. The matrix acts as the bonding element and its main function is to transfer and distribute the load to the reinforcement material. The transfer of load depends on the bonding between the matrix and the reinforcement. However, the bonding depends on the type of matrix and reinforcement as well as the fabrication technique. The matrix material is used in various forms for different fabrication methods, for example powder is used in powder metallurgy and liquid matrix material is used in liquid metal infiltration, squeeze casting and compo-casting. Matrix selection depends not only on desirable properties but also on which material is best suited for a particular composite manufacturing technique. The matrix should be chosen after giving careful consideration to the chemical compatibility with the reinforcement, its ability to wet, its own characteristic properties and processing behaviour [8].

Basically, the prime role of reinforcement material in the matrix is to carry load. The reinforcement (fibers, whiskers, particles) etc. increases strength, stiffness (toughness) and temperature resistance capacity. The correct selection of reinforcement type, geometry or shape is important in order to obtain the best combination of properties at substantially low cost. When selecting the reinforcement materials, the shape, size, surface morphology, structural defects, inherent properties (strength, moduli and density) and chemical compatibility with the matrix must be considered [9].

III. Concept of CMCs

Many pure ceramic materials are hard, wear-resistant and can withstand prolonged service at high temperatures. However, a major limitation of these materials is their inherent brittleness. The purpose of developing ceramic matrix composites (CMCs) is to improve the desirable properties (especially toughness) of ceramics by adding reinforcements and limiting their inherent weaknesses. Naturally, it is often found that there is an improvement in strength and toughness of ceramic matrix composites [10]. Hence, the development of CMCs imparts various improvements over ceramics such as: degree of anisotropy on incorporation of fibers, increased fracture toughness, elongation to rupture up to 1%, and higher dynamic load capability. The increase in toughness in CMCs can be explained by energy dissipation mechanism where fiber matrix debonding, crack deflection, fiber bridging and fiber pull-out are the common failure mechanisms. Some common examples of CMCs are: Continuous SiC fiber reinforced glass-ceramics, Zirconia-toughened and SiC whisker toughened alumina and Carbon-Carbon composites.

IV. Challenges

Monolithic ceramics can be used up to very high temperatures in the range of 1000°C to 2000°C with excellent creep resistance and high stiffness. However, the main disadvantage of monolithic ceramics is their low fracture toughness which leads to brittle fracture and detrimental thermal shock resistance. Hence, ceramic matrix composites are developed to overcome these challenges and maintain all the advantages of monolithic ceramics. Unfortunately, most of the composite components produced are currently too expensive for mass production due to the high cost of raw materials and the production time required. The cost of ceramic matrix composites (CMCs) strongly depends on composition and manufacturing route. It varies between some hundreds and thousands of dollars per kilogramme ($/kg). CMCs are expensive compared to other materials and the high price has to pay off by longer service life or by a unique performance in value-added products [11]. Alternative reinforcement phase morphologies have to be investigated in order to reduce the cost of ceramic matrix composites while retaining the attractive properties. This approach typically involves the use of less expensive, discontinuous reinforcement phase via powder metallurgy and casting techniques. The major reason for using particles is to reduce the cost of the composites. So the reinforcement has to be readily available in the quantities, size and shape required at low cost. It is certain that cost effectiveness of mass-produced composite components can only be achieved by using low cost, high reliability materials, new high-speed processing techniques and new structural design approaches [11].

Design methodologies, materials use philosophies, and durability data that will enhance material choice need to be developed. Improving material choice improves the economic viability of the class of materials. Economic viability assessments of composite joining and inspection technology is needed to determine whether reduced assembly costs (from parts consolidation) offsets the higher manufacturing cost (of large parts). It is clear that an aggressive research and development portfolio should be followed and several orders of cost reduction resulting from major breakthroughs are needed before composites become the material of choice for the automobiles makers [11].

V. Micro-Scale Particulate CMCs

There are materials which have metallic inclusions essentially within a ceramic matrix. However, the term micro-scale particles (metal) ceramic composite is usually taken to mean a material that has been designed such that the metal is in the form of inclusions that are isolated from each other (rather than forming a continuous network) and which deform plastically, thereby producing a toughening increment. There are examples of such composites e.g., tungsten in glass [12], molybdenum in alumina [13], iron, cobalt and nickel in magnesia [14], nickel and aluminium in glass [5]. An increasing interest in this group of materials developed in the late 1980s and early 1990s, a period during which a number of allied topics were being explored. Alongside this, there was the development of ceramic composites produced by directed metal oxidation which tended to give materials a continuous or partially continuous network of a metallic phase. When a particulate (micro) second phase is introduced into a brittle matrix, there are several toughening mechanisms that may operate but the maximum benefit is derived from the micro-metallic particles if they are able to deform plastically and bridge an advancing crack. This is easy to achieve in systems in which the metallic phase is (partially) continuous e.g. traditional cermet such as tungsten carbide-cobalt and the directed metal oxidation products. However, it is not always desirable to have an interconnected metallic phase, hence the development of composites containing discrete metallic particles. Thus, an ideal particle ceramic composite comprises micro-metallic particles within a ceramic matrix such that an advancing crack is attracted to a particle. The particle then debonds partially from the matrix, ideally to its polar regions and deforms plastically, thus absorbing energy and bridging the crack, providing closure tractions both of which will provide a toughening increment [15].

Putting this concept into practice poses several challenges and has resulted in a wide range of materials with some interesting properties. Particles are the most common and cheapest reinforcement. This type of reinforcement material produces discontinuous reinforced composites with isotropic properties. Another advantage is that conventional fabrication methods may be used to produce a wide range of product forms, making them relatively inexpensive compared to composites that are reinforced with continuous fiber or filaments. Particle shape and size play an important role since angular particles can act as stress raisers, whereas rounded or globular particles are favoured for the impact properties. Spherical particles give better ductility than angular shapes [15]. Fine particles are more effective in strengthening the composites than coarse particles of the same volume fraction [16].

Optimising composite development ought to include considerations of all the fundamental aspect of particles including their shape, size, volume fraction and mechanical properties. Most of the works on micro-scale composites are on alumina matrices, although other systems have been investigated, including glass with molybdenum or vanadium particles [17], glass with copper particles [18]. Glass-ceramics with the followings: silver [19], molybdenum [20], copper [10], iron [21] and chromium-nickel [22]. Alloys were popular choices for the metal inclusions as they offered the dual benefits of favourable properties and compatibility with the matrix. Many authors quote fracture toughness values in the region of 3-9 MPa, which equate to ratio of fracture toughness of the composite to that of the monolithic matrix in the range slightly over 1 to 3. Most of these values have been derived from indentation crack lengths. There have been attempts to add two types of second phase particles in the anticipation that there will be some synergy between the toughening mechanisms. Thus, silver and zirconia were added to alumina [23]. An increase in toughness was achieved in the early studies and the toughening increment was less than the sum of the increments expected for the two mechanisms acting separately. In the composite containing both toughening agents, the zirconia particles failed to transform as the silver inclusions which were embedded in the zirconia aggregates. Subsequent improvements in the processing to avoid the formation of zirconia aggregates did result in composites in which the two toughening increments were additives but there was no further increase [16]. Both titanium carbonitride and zirconia have been used as reinforcing particles within alumina for the manufacture of cutting tools tips with higher hardness and better tool wear resistance characteristics.

VI. Mechanical Properties of CMCs

Typical mechanical properties of ceramic composites are:

- Tensile and compressive behaviour
- Fracture toughness
- Creep resistance
- Resistance-Curve (R-Curve) Behaviour
- Fatigue resistance

These are important mechanical properties which have to be investigated before advocating the use of a ceramic matrix composite for a particular application. Because, there are large number of combinations of matrix and reinforcement available to develop ceramic matrix composites, one cannot discuss the mechanical properties of each and every combination showing or indicating how it would behave under various loading environments. But, in general, good bonding (adhesion) between matrix and dispersed phase provides a high level of mechanical properties of the composite via the interface [5].

A. Tensile and Compressive Behaviour of CMCs

Tensile and compressive behaviour of ceramic matrix composites can be explained with the help of stress-strain curve. When testing of a ceramic material is being carried out, stress strain is obtained as shown in Fig. 1.

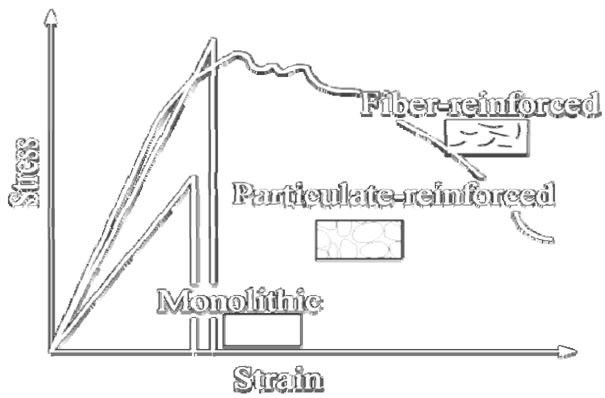

Fig. 1 Stress-strain curve for ceramic materials

There would be a sudden failure for a monolithic ceramic material. In case of ceramic matrix composites, ceramic matrix is reinforced with different reinforcements (particulate and continuous fiber reinforcement). For particulate ceramic matrix composites, it shows a higher stress to failure as compared to the monolithic ceramics as shown in Fig. 1. For continuous fiber reinforced ceramic matrix composites, there is no sudden or catastrophic failure. The failure is a non-catastrophic type and there is a certain percentage of elongation in fiber reinforced ceramic composites which improve the fracture toughness of the material. Tensile tests of CMCs usually show nonlinear stress-strain curves which look as if the material deforms plastically. It is called *quasi-plastic*, because the effect is caused by the micro-cracks which are formed and bridged with increasing load. Because the Young's modulus of the load-carrying particles is generally lower than that of the matrix, the slope of the curve decreases with increasing load. Curves from bending tests look similar to those of the crack resistance measurements.

B. Fracture Toughness of CMCs

The primary quality criterion for metal-particle-reinforced ceramic matrix composites (MPCMCs) is the crack resistance behaviour or fracture toughness. One of the advantages of these materials is their increased fracture toughness compared to that of traditional ceramic materials [24]. This parameter depends on some factors such as: the type, volume fraction, size and shape of metallic phase particles and also on uniformity of their distribution within the matrix of a composite [25]. Fracture toughness is the limitation for ceramics. But, in case of ceramic matrix composites, fracture toughness improves due to reinforcements. How toughening takes place and improves fracture toughness in case of reinforced ceramics (which is better as compared to monolithic ceramics) can be explained with the help of toughening mechanisms [25].

C. Toughening Mechanisms

As fracture toughness of ceramic matrix composites is higher as compared to monolithic ceramics, it is important to look at different toughening mechanisms to know why and how toughening is taking place due to fiber reinforcement. The schematic explanation of these mechanisms is shown in Figs. 2 (a)-(c). There are basically three main toughening mechanisms: crack impeding, fiber/whisker pull-out and crack deflection.

D. Crack Impeding

It is basically crack arresting mechanism. Arresting of cracks takes place because fracture toughness of fibers is greater than that of the matrix. Crack may propagate in the matrix but it will not be able to tear open the fibers and thereafter propagate through the fibers.

E. Fiber (or Whisker) Pull-out

The reinforcement can be in terms of fibers or whiskers and these may be pulled out of the matrix. Fibers have high transverse fracture toughness which causes failure along the fiber/matrix interface due to pulling out of fibers from the matrix.

F. Crack Deflection

Weak fiber/matrix interfaces deflect the crack.

G. Creep Resistance of CMCs

It is a function of stress, time and temperature. For any given material, it occurs by diffusion, dislocation motion, grain boundary sliding, or softening of grain boundary phases. The presence of the second phase can have a significant effect, either positive or negative, on the rate at which a material creeps. Many ceramic composites which contain glass have poor creep resistance because glass enhances grain boundary sliding. In case of some whisker-reinforced ceramic composites (e.g. SiC whisker in Si_3N_4) no improvement in creep behaviour was reported [26].

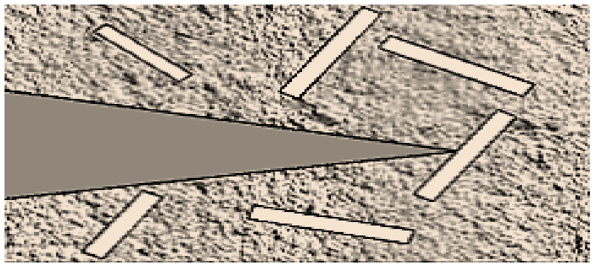

Fig. 2 (a) Crack impeding

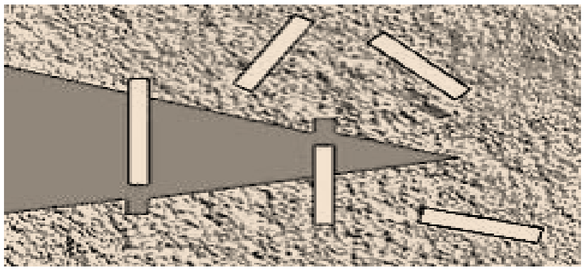

Fig. 2 (b) Fiber pull-out

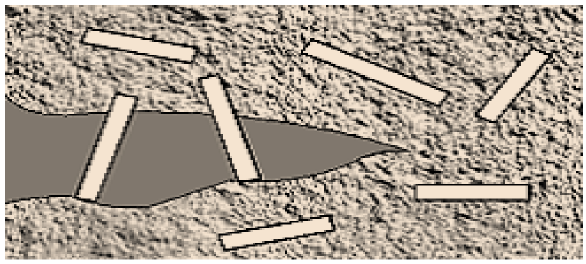

Fig. 2 (c) Crack deflection

H. Resistance-Curve (R-curve) Behaviour of CMCs

For a given material, R-curve behaviour exhibits resistance to crack propagation which increases with increasing crack length. For any material, R-curve is an important characteristic in terms of the mechanical performance because it defines a degree of tolerance of the material. Therefore, the strength of the materials becomes insensitive to the flaw size. As shown in Fig. 3 in the study to determine the rising crack-growth-resistance behaviour of Al_2O_3 based ceramic composites toughened with Fe_3Al intermetallic particles, it can be seen that the R-curve was strongly influenced by the Fe_3Al particles addition. Significant improvements in the crack growth resistance were achieved by the addition of Fe_3Al particles and this led to more pronounced R-curve behaviour than unreinforced Al_2O_3 [26].

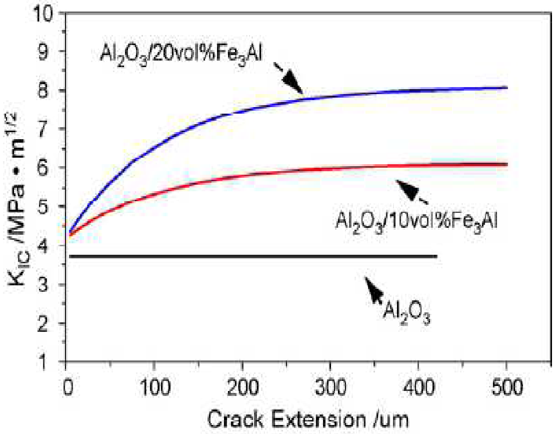

Fig. 3 R-curves of unreinforced and reinforced samples of Al_2O_3 ceramic composites

I. Fatigue Resistance of CMCs

In case of cyclic loading of ceramic based products, if there is a minor crack, it may propagate rapidly and sudden failure may occur. In case of fiber reinforced ceramics, cracks may be arrested by the reinforcement in ceramics and failure can get delayed. Therefore, the fracture toughness of ceramic matrix composites has to be investigated in order to find the number of cycles to failure for a particular product. Significant progress has been made in understanding the crack growth resistance and strength behaviour of metal particles reinforced ceramic matrix composites (MPCMCs) and other ductile phase reinforced brittle systems subjected to mechanical loads. For an advancing crack to be attracted to an inclusion, rather than being repelled by it, the elastic modulus of the inclusion must be lower than that of the matrix. This is not a problem for most engineering ceramic/metal combinations. The toughening should increase with the volume fraction and yield strength of metal particles. There is, however, a limit to the amount of metallic phase that can be added if the particles are to remain isolated from each other and hence contribute effectively to the toughening [27]. However, if the inclusion becomes too large the difference in the coefficients of thermal expansion of the metal and the ceramic matrix is likely to result in cracking. This may lead to an advancing crack being able to by-pass the particle [27].

VII. Thermal Stability of CMCs

Monolithic ceramics are very sensitive to thermal stress because of their high Young's modulus and low elongation capability. Temperature differences and low thermal conductivity create different elongations, which together with the high Young's modulus generate high stress. This results in cracks, rupture and brittle failure. In ceramic composites, the particles bridge the cracks and the components show no macroscopic damage, even if the matrix has cracked. The application of ceramic composites in brake disc demonstrates their effectiveness under extreme thermal shock conditions. Thermal stability is important for an application where the component is often subjected to thermal cycling, or when the material cannot be allowed to expand (where close tolerances are needed). It is also important to have small differences in the coefficients of thermal expansion (CTE) when different materials are combined to avoid internal stress and thermal mismatch strain being generated in the composites [17]. The CTE of the composite depends on the volume fraction of the reinforcement and CTE normally decreases with increasing particle content [18].

The thermal crack shielding and shock damage in a double-edge cracked metal particle reinforced ceramic composite subjected to sudden cooling at the cracked surfaces was studied. Under severe thermal shocks, the crack will grow but will be bridged by the plastically stretched metal particles. A linear softening bridging law is used to describe the metal particle bridging behaviour. An integral equation of the thermal crack problem incorporating the bridging effect is derived and the thermal stress intensity factor at the bridged crack tip is calculated numerically. It is found that the thermal stress intensity factor is significantly reduced by the metal particle bridging. While the crack growth in thermally shocked monolithic ceramics is unstable, the metal-particle-reinforced composite can withstand sufficiently severe thermal shocks without failure [28].

VIII. Conclusion

Ceramic composites which are reinforced with particles are emerging as a class of advanced engineering structural materials. Research has shown that low fracture toughness and poor crack growth resistance can be overcome by reinforcement with particles. Micro-particles reinforced ceramic composites are unique because they combine low density with high modulus, toughness and strength retention at high temperatures when compared with monolithic ceramics. Their intrinsic ability to be tailored as composites make them to be highly attractive in a vast array of applications, most notably internal engine components, exhaust systems and other “hot-zone” structures, where they are envisioned as lightweight replacements for metallic super alloys. Their application in brake disc demonstrates their effectiveness under extreme thermal shock conditions. They also have better corrosion and erosion characteristics for high temperature applications with lower cost of production. These unique characteristics provide the engineer with design opportunities not possible with monolithic ceramics.

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