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# Underwater shock consolidation of Mg–SiC composites

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**Abstract** The shock consolidation of magnesium (Mg)/silicon carbide (SiC) composites using axisymmetric explosive fabrication setup is reported. Pure Mg and SiC powders are consolidated in a three-layered cylindrical assembly with the energy being derived from a high-detonation velocity explosive. The pressure of underwater shock wave is experimentally measured and simulated using AUTODYN 2D. Microstructural characterization of the samples revealed a well-flown Mg matrix enveloping near homogeneous SiC particles. Occasional clustering of SiC particles and interparticle melting is evidenced. Results of microhardness revealed that the presence of SiC particulates led to a substantial increase in the hardness of the composite. Fractography results indicate the lack of formation of ductile dimples, which is attributed to the presence of discontinuous SiC particles. The strengthening mechanism, the absence of reaction products, the structure–property correlation of the shock consolidated composite are discussed.

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## Introduction

The design of components in the applications of aerospace, electronics, medical, and other spectrum of high-tech industries demands the development of advanced materials such as discontinuously reinforced metal matrix composites (MMCs). These composites can offer distinct technological advantages over continuously reinforced MMCs and show significant improvement in properties over monolithic alloys [1, 2]. The most notable has been the increase in specific properties such as stiffness and strength. Nonetheless, these improvements are accompanied by a general degradation of the fracture properties such as ductility and fracture strength [3]. In recent years, magnesium (Mg) with its $\sim 35\%$ lesser density, as compared to aluminum, holds promise as a viable alternative engineering material which requires higher specific mechanical properties. Adding ceramic particle reinforcement can easily compensate the major limitation in terms of the low modulus of elasticity of Mg and its alloys. An improvement in tribological properties, dimensional stability, damping capacity, elevated creep properties, and improved elastic properties can be achieved by the judicial consideration of the physical parameters of the reinforcement and the Mg matrix [4].

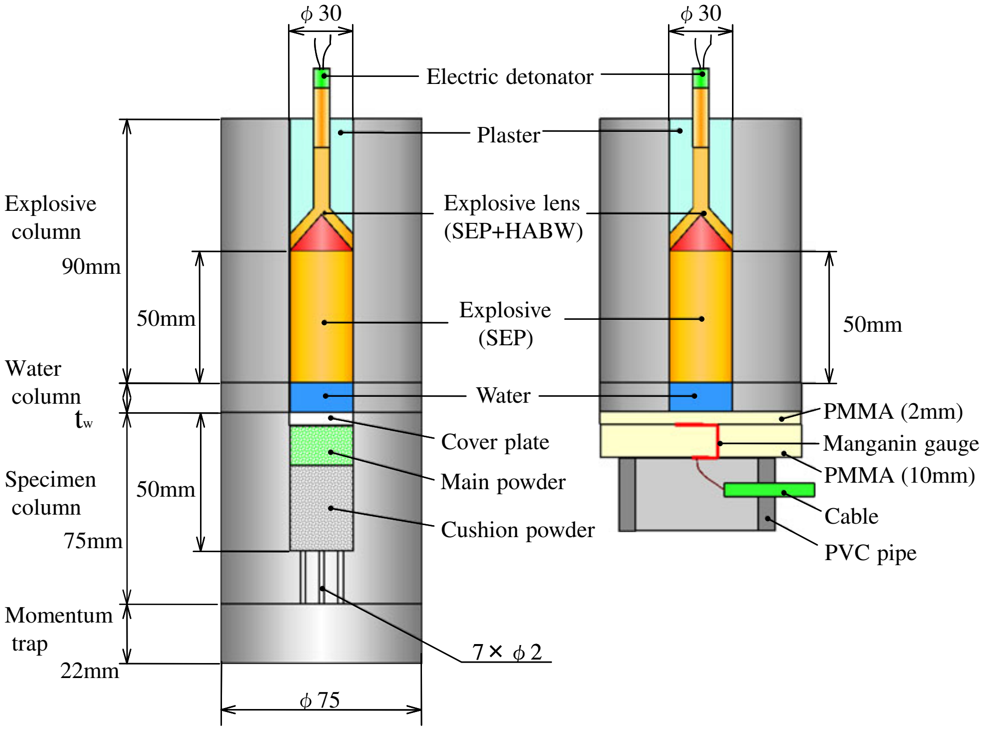
Mg-based composites can be produced by various techniques namely, stircasting, squeeze casting, spray forming, and powder metallurgy routes. A key challenge is to obtain homogeneous distribution of the reinforcement particulates with least or no reaction intermetallics so as to achieve a defect-free microstructure. Magnesium wets well with ceramic reinforcements than aluminum and its reactivity with reinforcements is high [5]. Hence, the shock consolidation route—a one-stage densification process which involves very rapid and intense deposition of shock energy on powder particle surfaces [6–8]—was preferred. Shock consolidation, utilizing the preferential deposition of energy of powders, is a low-temperature consolidation technique, which imposes extreme pressures and temperature gradients on materials in microseconds [9]. The shock wave can be produced by high-velocity impact of projectile using a gas gun in which shock pressure can be easily controlled by changing the impact velocity, or by explosives in contact with powder container [6, 7] in which the desired range of shock pressures can be varied by changing the type of explosive and the fixture geometry. Explosive compaction, using water column to transmit shock waves to consolidate loose powders, provides the ability to employ a more dispersed shock wave of prolonged pulse duration to attain full density compacts by providing an increased time for interparticle bonding. The process parameters, variations, advantages, and applications of this process are discussed in detail in earlier reports [6, 7]. The characteristics of the shock consolidated Mg/SiC composites are reported.

## Experimental procedure

The bulk composite was fabricated using commercially pure magnesium (99% pure, 100 mesh) and mono-sized (3000 mesh) SiC particle reinforcement. The mass percentage of SiC particles added with the matrix was 10–40%. The composite powders were mixed and statically pressed to packing density 60% of theoretical maximum density in a shock consolidation capsule in an argon ambience. The shock waves, generated using a planar impact system by the use of an explosive lens [6, 7], were uniformly applied on the powder blend (Fig. 1). The planar impact system was made by a combination of two explosives, namely SEP and HABW (both of Asahi-Kasei Corp., Japan; Detonation velocity: 6.97 and 4.75 km/s, Density: 1310 and 2200 kg/m$^3$, respectively). Varying the height of the water column ($t_w$) can regulate the shock pulse. A layer of aluminum powder acted as a shock absorber. The stacking arrangement and the explosive lens for the planar shock wave system have been reported elsewhere [6, 7]. The bulk composite was sectioned and subjected to microanalysis.

The peak pressure value and the pressure profile of underwater shock pressure are vital in determining the optimum conditions of the compaction process. Hence, numerical simulations using AUTODYN-2D were performed, as axisymmetrical problem with all parts modeled using Lagrange Solver, to determine the pressure distribution at the water container just above the cover plate. Manganin gauges were located on the water container at intervals of 5 mm (Fig. 1) to track the shock wave and were attached on to the PMMA sheet placed beneath the water container. Figure 2 compiles the simulated pressure profile of planar shock wave as a function of time. Figure 3 shows the comparison between the experimentally measured pressure values and those obtained from AUTODYN

**Fig. 1** Schematic arrangement of the explosive compaction setup and the test setup for pressure measurement



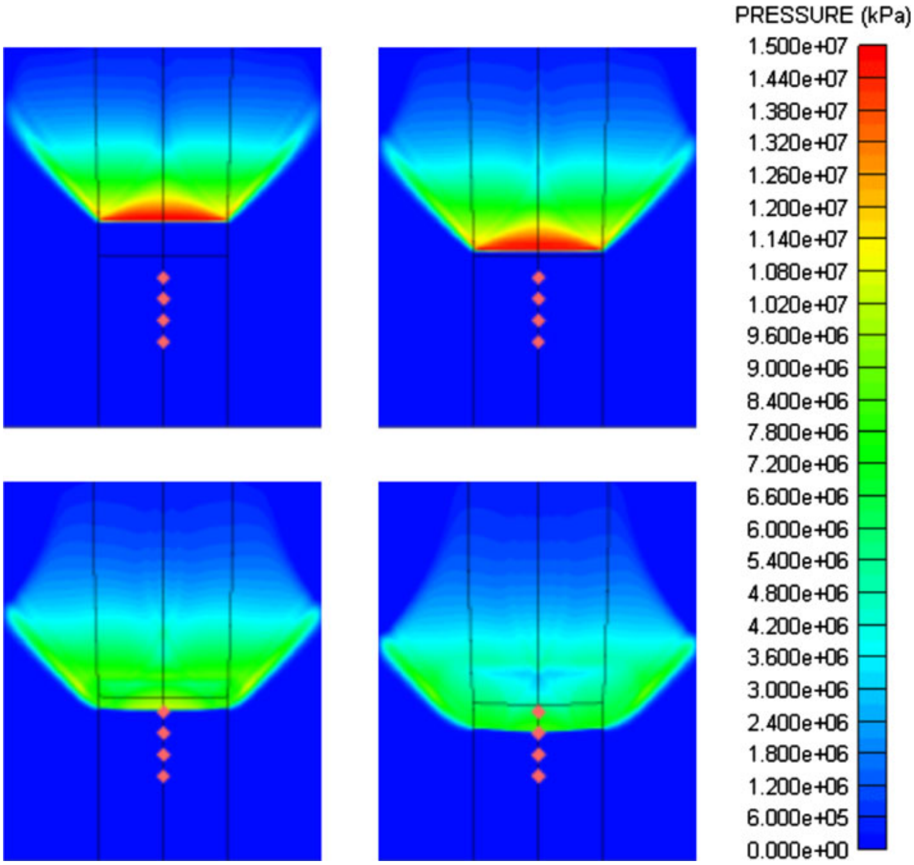


**Fig. 2** Simulated pressure profile of underwater shock wave

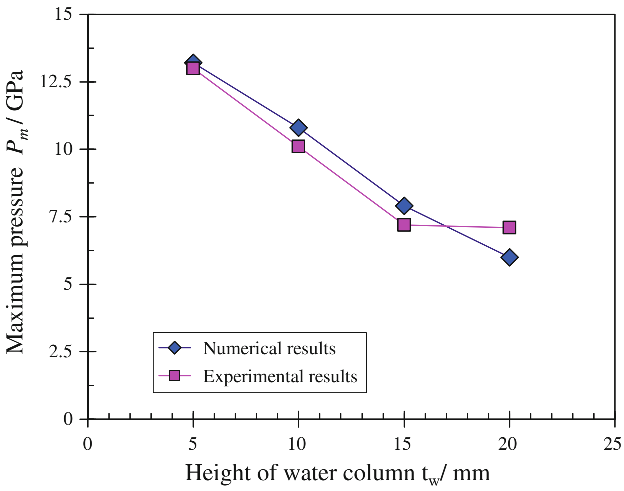


**Fig. 3** Simulated versus experimental pressure profiles of underwater shock wave

simulation. It can be seen that the simulation results are in close fit to the experimental data. The simulation results are similar to the values calculated by finite difference analysis method [6]. The shock pressure is 13.0 GPa at $t_w = 5$ mm and decreases with increasing $t_w$. Hence, the experiments were conducted by fixing the water column as 5 mm.

## Results and discussion

Optical microstructural observations of the shock consolidated Mg–SiC composite were, primarily, made to substantiate the distribution of the ceramic particles in the metal matrix, the presence or absence of clusters and agglomeration of particles, the presence of any inclusions and voids, and the integrity of the interface frontier. The optical micrographs of the composites revealed a well-flown, ductile, recrystallized Mg matrix grains enveloping near homogeneous distributed SiC particles (Fig. 4). The flow of matrix is smooth, and occasional clustering of particles is evidenced (Fig. 5, indicated by arrows). The matrix grain morphology is more or less elongated in the direction of plastic deformation and the size being non-uniform. The interfaces are sharp with integrities intact and good with the absence of large voids and reaction products.

Seshan et al. [10] stated that the lack of formation of ductile dimples, as the ductile dimple mode, is essentially contributed to be due to the constraints on the plastic flow by the presence of discontinuous SiC particles and not due to the limited ductility of the Mg matrix alloy. In the particle strengthened composites, the role of the matrix is as an intermediate load-bearing constituent, while the role of the dispersed phase is to constrain the matrix, thereby,

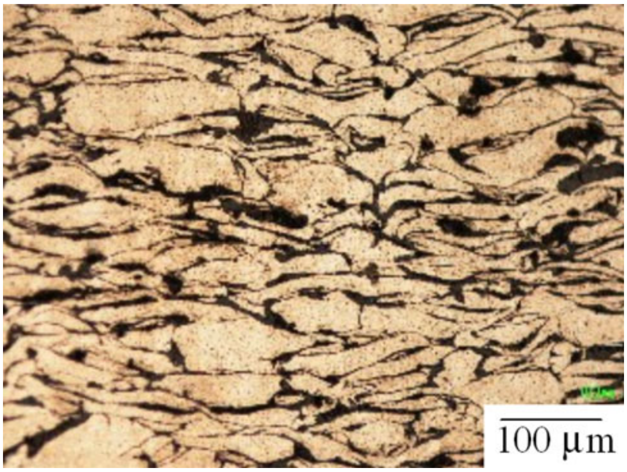


**Fig. 4** Optical micrograph of 10% mass SiC–Mg composite

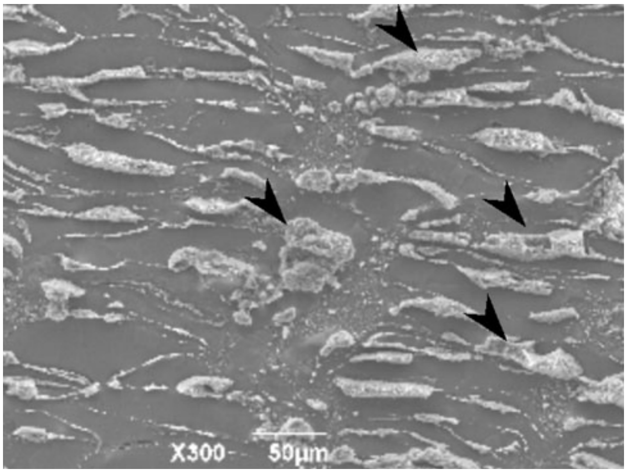


**Fig. 5** SEM image of Mg–SiC composite showing particle clusters

increasing the strength of the composite. While the strength mainly depends on the volume fraction, property of the constituents and the processing routes, the characteristics of the interface between the matrix and the reinforcement are very crucial [11]. The distribution and transfer of load from the matrix to the reinforcing phase is effective with a well-bonded interface [12]. The cracks in the ductile matrix occur when the local fracture stress exceeds the fracture strength of the matrix, but is lower than the fracture strength of the interface and that of the reinforcing phase. As the interface is stronger the load transfer becomes more effective, furthering the strengthening of the composite. The absence of the brittle reaction products is also supplementary to the strengthening mechanism and leads to improved composite strength. In addition the cracks, observed in the fractograph (Fig. 6), are not seen to extend across the specimen and are found to be discontinuous and discrete.

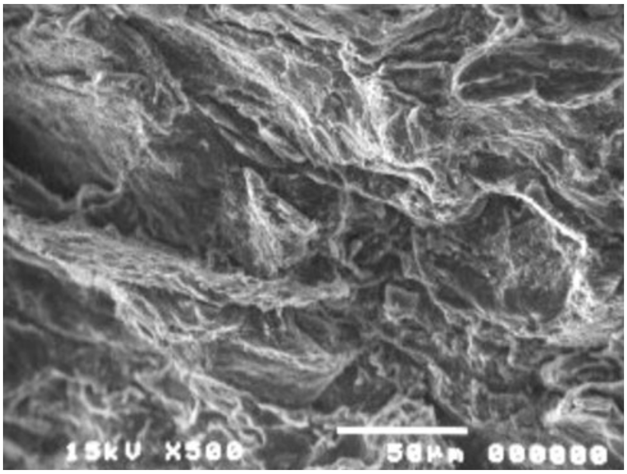


**Fig. 6** Fractrography of Mg–SiC composite

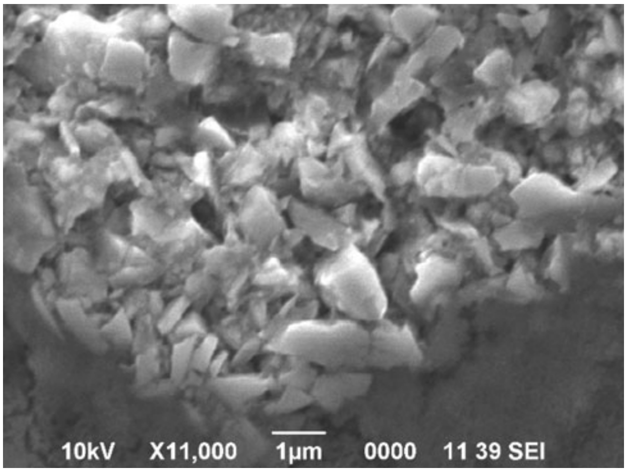


**Fig. 7** SEM image of SiC particles at the interface in a 30% mass SiC–Mg composite

Though the interfacial bonding between the matrix and the reinforcement can be chemical and or mechanical [11], mechanical bonding mechanism is possible in shock consolidation mainly due to the extremely short processing time. Mechanical bonding results in greater constraint on matrix deformation, which in turn leads to stronger interface bonding. Feest [13] opined that the mechanical interlocking effect is capable of yielding very strong interfacial bonds.

The fractograph shows ductile flow of matrix, with no prominent dimples. Cleavage facets are seen to be increasing with the increasing presence of the SiCp reinforcements, indicating the inclination of the tendency of fracture toward brittle. Voids, nucleating from grain edges, are not observed, thus inferring, appropriate solidification. Cracks, very minor in nature, are seen, but not extending throughout, thereby, indicating the absence of any weakening mechanisms in the composite and also indicates the presence of internal stresses as a resultant of the property disparity of the participant materials.

Figure 7 shows the agglomerated particles at a region very close to the interface, with the larger prevalence of fractured or decohered particles at the agglomerations. The agglomerated site consists of few larger SiC particles intermingled with fractured and cracked brittle counterparts. The enhanced local stress developed from the restrictions of plastic deformation and the inherent brittleness associated with the reinforcement particles result in the particle cracking aided by cohesion or separation, leading to a general reduction in ductility as observed in the changes in hardness profiles.

The disparity in the co-efficients of thermal expansion between the matrix and reinforcement material, resulting in heterogenous deformation, significantly alters the strength of the composite [10]. The hydrostatic pressure, present due to the existence of the particles, increases the stress required to produce plastic deformation in the matrix and thereby, enhances the strength characteristics of the resulting composite [14]. The hardness profiles, observed across the sectioned consolidated composite, are in agreement (Fig. 8).

In contrast to conventional pressing processes of metal and ceramic powders, explosive compaction is enabled by shock waves originating from explosives. A converging shock wave travels into the powder with a tap density of about 50% and due to the high-shock pressure leaving fully compacted material behind, in most cases 100% of theoretical density [15]. The process is considered adiabatic and irreversible. Energy deposited in the process is dissipated as heat at the surface of powder particles where surface melting can take place leading to fusion welding of individual powder particles. Nonetheless, for systems involving metals and ceramics the interdiffusion of species from the two components can produce an interfacial layer of different composition and structure from either of the components. The interface layer will have different mechanical properties from either of the matrix or reinforcement and this greatly influences the interface [16]. In case of Mg–SiC composite system, the possible reaction can be written as

$$\mathrm{Mg} + \mathrm{Si} \rightarrow \mathrm{Mg_2Si} \tag{1}$$

and

$$4\mathrm{Mg} + \mathrm{SiO_2} \rightarrow \mathrm{Mg_2Si} + 2\mathrm{MgO} \tag{2}$$

The reaction products are very sensitive to corrosive environment rendering the composites inapplicable to commercial exploits. The diffusion of the brittle precipitates is rapid at high temperature as the rate of diffusion, or the diffusion coefficient, $D_\mathrm{d}$, increases exponentially with the temperature according to Arrhenius-type equation

$$D_\mathrm{d} = D_\mathrm{o}\exp(-Q_\mathrm{d}/RT), \tag{3}$$

where $Q_\mathrm{d}$ is the activation energy for diffusion, $D_\mathrm{o}$ is a constant, $R$ is the gas constant, and $T$ is the temperature [17]. The primary advantage of shock consolidation is that it being a rapid process the consolidation of powder to fully solid density occurs by the passage of shock waves of sufficient amplitude with in a very short interval. As the time consumed is on the order of $50 \times 10^{-8}$ s [18], the formation of the brittle precipitates of reaction material is essentially decelerated.

The microstructural findings reveal no oxidation of Mg and no detectable reaction between Mg–SiC, thus suggesting the lack of oxygen as reported by Manoharan et al. [4]. The X-ray diffraction on the compact was performed using a Shimazdu XRD-600 diffractometer. The samples were exposed to Cu K$\alpha$ radiation for the phase identification at a scanning speed of 2°/min. The X-ray diffraction intensity of Mg and SiC is strong and pronounced. The peak of the interaction layer is absent. Kaneko et al. [19] reported the formation of MgO only when Mg is heated to 773 K and stated the formation of $\mathrm{Mg_2Si}$ which is triggered considering the fact that SiC contain free silicon and often associated with a thin layer of $\mathrm{SiO_2}$. Nevertheless, the absence of any reaction products suggests that the time of shock consolidation is insufficient to excite a reaction and the absence of a reaction product indicates the inability of Mg to form a reaction product with SiC. The energy of the shock released during the shock consolidation process is utilized in plastically deforming or fracturing the powder particles, and reducing the void volume to virtually zero. This gives rise to the preferential heating of particles spaces, which can cause melting and interparticle bonding [9]. Shtertser [20] proposed an expression based on the idea that microkinetic energy is the main parameter determining the possibility for bonding between particles. For the

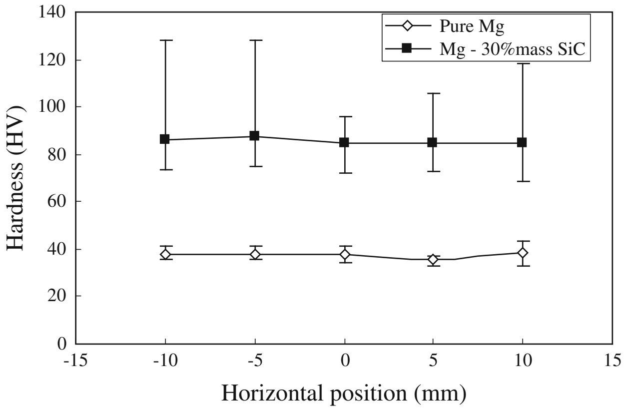


**Fig. 8** Microhardness traverse across the shock consolidated Mg–SiC composite

minimum pressure, $P_b$, to obtain bonding, taking into account not only the hardness of the materials and its distension, $\alpha$, but also the influence of an oxide layer on the particle surface

$$P_b = k^2 H_V / (\alpha - 1), \tag{4}$$

where $k$ depends on oxide layer thickness $\delta_o$. It can be deduced that the pressure, $P_b$, required for bonding between particles in the explosive consolidation process is considerably lesser than that required by other methods of consolidation.

As the powder particles are normally covered with oxide layers, the formation of bonds between them requires high temperature or mechanical removal of the contaminant layers by fracture or plastic deformation. The plastic deformation in powders occurs at pressures beyond the Hugoniot Elastic Limit (HEL) of the material [21], it is, however, likely that due to many contact with a powder, this pressure will locally be surpassed at much lower shock wave pressure.

Taking these into consideration, it can be deducted that the explosive pressure required to shock consolidate powdered composite is less than that required to consolidate powdered composite by conventional routes and that shock consolidation technique is capable of producing defect-free Mg–SiC composites.

## Conclusions

Underwater shock consolidation using axisymmetric assembly, derived from a high explosive, was used to fabricate Mg–SiC composites. The pressure of underwater shock wave simulated using AUTODYN-2D is in close fit with the experimental results. Manifestations of well-flown matrix enveloping a near homogeneous ceramic particles with a clear and sharp interface, proved shock wave consolidation to be a promising technique to produce Mg–SiC composites. Occasional clustering of particles is evidenced. Representative hardness measurements show a substantial increase in hardness of the composites. Lack of formation of ductile dimples in the fractography of composite is attributed to the presence of discontinuous SiC particles.

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