Experimental and numerical study on penetration of micro/nano diamond particle into metal by underwater shock wave

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ABSTRACT
In order to develop composite materials, new attempting was conducted. When an explosive is exploded in water, underwater shock wave is generated. Metal plate is accelerated by the underwater shock wave and collided with diamond particles at high velocity. In this paper, pure aluminum and magnesium alloy plates are used as matrix. Micro and nano sized diamond particles were used as reinforcement. Micro diamond particles were closely coated on metal surface. Some of micro diamond particles were penetrated into aluminum. Improvement of base metal property (wearing resistance) was verified by wear test for recovering metal plate. In order to confirm the deformation of the aluminum plate during the collision with diamond particles, simplified numerical simulation was conducted by using LS-DYNA software. From the result of numerical simulation, large deformation of aluminum and process of particle penetration were verified.

Keyword: composite materials, explosive, underwater shock wave, diamond, LS-DYNA

1. INTRODUCTION

In material processing using explosive, explosive welding [1] and explosive forming [2] have been industrialized. Explosive powder compaction [3] and synthesis [4] have been researched by some authors. These techniques have possibility to make a new material and highly functional materials [5]. In order to recover large sized bulk composite, authors have investigated explosive powder compaction using underwater shock wave. Water is medium, which can propagate a uniform pressure. Also, influence of heat generated from explosion can be reduced by water. Authors suggested explosive underwater shock wave method for material processing [6]. The method proposed here is to implant diamond particles on metal surface by using underwater shock wave. Metal plate is accelerated to high velocity and

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collided with diamond particles. Some diamond particles penetrated into metal, composite layer is formed at closed metal surface. Diamond is not only hard material but also has high thermal conductivity. It is expected that wear characteristics and thermal properties of the base metal a improved by implanting or penetrated diamond particles. It is well known that producing an aluminum-diamond composite is very difficult through conventional materials processing technology, which uses heat-treatment, because of the reaction for making intermetallic like Al_4C_3. On the other hand, the use of an extremely rapid process like shock wave processing should be a very favorable process for making such non-equilibrium composites, though the method is still under investigation. The use of a solid plate, instead of using powders, as matrix is considered easier to obtain composites having improved mechanical properties, especially on the surface. Therefore, a new method to make a surface composite layer on a surface of a substrate plate is proposed and investigated through micro structural characterizations.

2. EXPERIMENTAL PROCEDURE

Schematic of the developed method is shown in Fig.1 Experiments were conducted by using water as a media for explosion. The explosive was produced by Kayaku Japan Crop and the detonation velocity is about 7000 m/s and the density is 1310 kg/m. The explosive was produced from 5 mm thickness plate together whit pasted PMMA on it. Initiation was carried out by No.6 electric detonator produced by Kayaku Japan Crop.. Sample composed of tow metal plates including 1.5 mm-thick industrial pure aluminum JIS-A1050 and 1.5 mm-thick magnesium alloy JIS-AZ31, diamond powder and silicon tape. Fig. 1 shows the upper and lower plates as s flyer and base plate respectably. In this study, two types of diamond powder particles were used, one is micro sized diamond whit the average diameter of 15 μm) and the other is nano sized white the average diameter of 10 nm diamond. Both of them were used as abrasive powder. White the different morphological characteristics; i.e. Micro diamond particle has sharp edges, while nano diamond particle has spherical shape. Silicon tape was

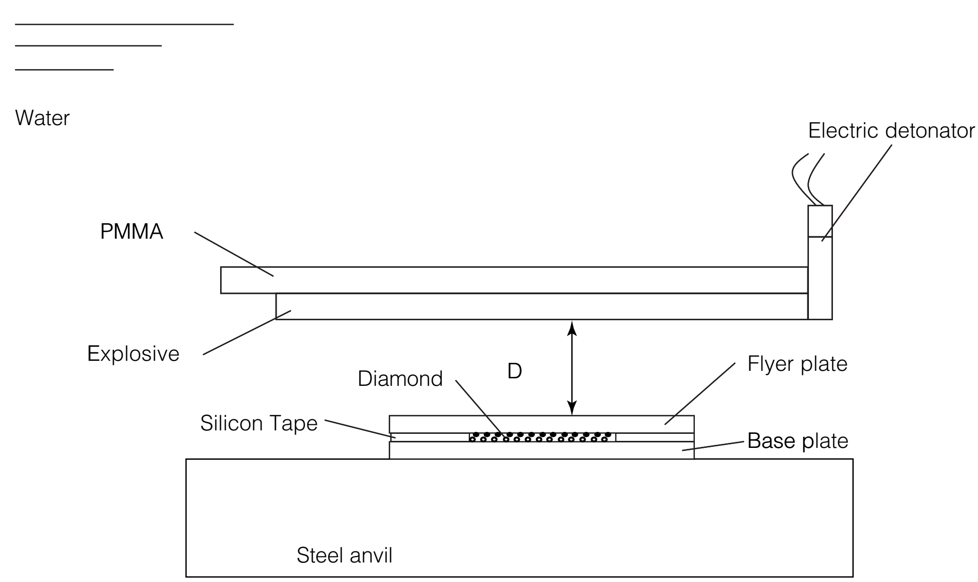


Fig.1 Schematic of developed method by using underwater shock wave.

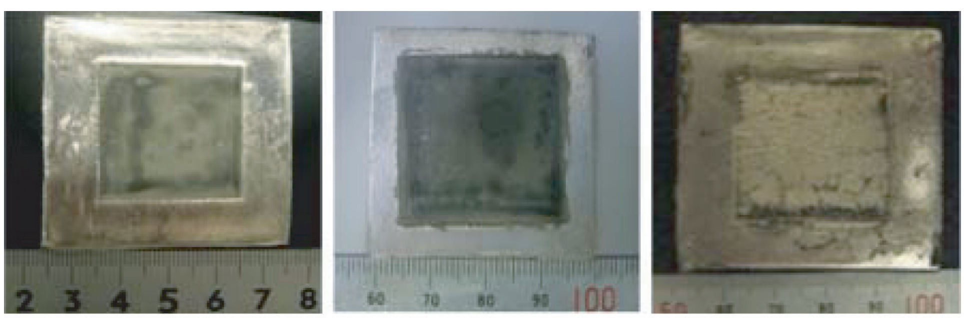
Table 1 experimental conditions

No.	Flyer plate	Base Plate	Powder	D (mm)
1	JIS-A1050	JIS-A1050	Micro diamond	30
2	JIS-AZ31	JIS-AZ31	Micro diamond	30
3	JIS-A1050	JIS-A1050	Nano diamond	30

used as water seal, and the thickness is 0.5 mm., therefore the gap between the plates was 0.5 mm. The sample was placed on steel anvil. There is a distance from explosive to sample as shown in Fig1 D, in order to easy control of shock pressure by changing the D. In table 1, the experimental conditions have been reported.

3. RESULTS AND DISCUSSION

Particles which not buried on metal surface were removed from flyer surface by ultrasonic washing machine. The recovered flyer plates after process of ultrasonic are shown Fig.2. Micro diamond particles were coated on metal surface although it is impossible to observe with naked eye. It is considered that nano diamond is easy to compact during the collision with aluminum plate, because of the very fine size and spherical shape. Fig.3 shows SEM of upper surface of recovered No. 1 flyer plate. it can be seen that micro diamnd particles were



No. 1 No. 2 No. 3

Fig. 2 Recovered flyer plates.

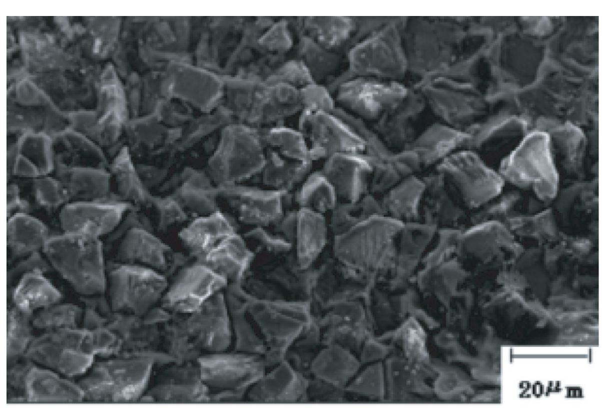
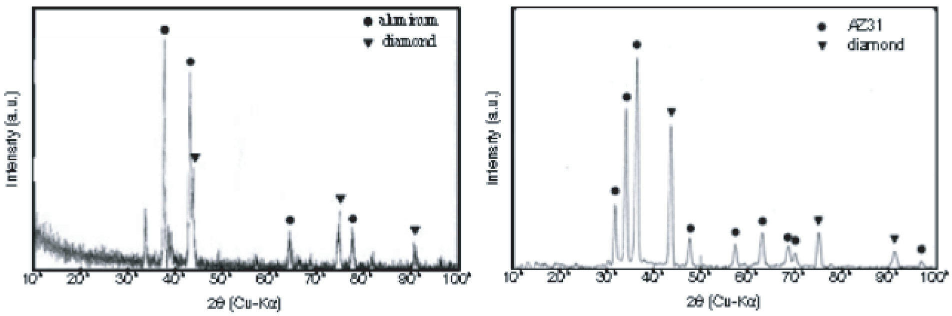


Fig. 3 SEM of upper surface of recovered No.1 flyer plate.



No. 1 No. 2

Fig.4 X-ray diffraction pattern (Cu-Kα).

closely coated on aluminum surface.

Fig. 4 shows the X-ray diffraction pattern (Cu-Kα) for the recovered No. 1 and 2 flyer plates taken from the upper surface. XRD results show that there is no reaction product observed. No significant peak broadening was observed. X-ray analysis for No. 3 flyer plate also shows there is no diamond peak in XRD patter. Cross section microstructure of recovered No. 1 and 2 flyer plates was observed by using optical microscope. Penetrated micro diamond particles were observed from No. 1 sample [7].

In this research work, it is expected to improve wear characteristic of sample surface and wear test. Wear test was conducted by using wear test machine produced by RHESCA Crop.. In this respect, No. 1 and 2 recovered flyer plates were fixed on rotation table, and applied load via stainless steel ball. Mass of recovered flyer plates was measured before and after the wear test. Table 2 shows wear test conditions and the results of it. Improvement of wear characteristic is confirmed from the results.

In order to investigate the deformation of aluminum during collision between aluminum and particles, a simplified numerical analysis was conducted by using LS-DYNA, numerical analysis software. This time, an analytical problem was replaced to two-dimensional (2D) problem. An SPH [8] method was applied for this simulation. SPH differs from the lattice approach used in a conventional finite difference method and the conventional finite element method. SPH transposes a lattice to a particle and analyzes it. SPH allows a stable analysis for large deformation process compare to that conventional method. Three types of

Table 2 conditions and results

Sample	Load (g)	Mass shinkage (mg)
JIS-A1050	30	1.4
	100	7
	200	21
No. 1 JIS-A1050 + micro diamond	30	0.2
	100	0.2
	200	.01
JIS-AZ31	30	1.8
No. 2 JIS-AZ31 + micro diamond	30	0.1
	100	0.1
	200	0.1

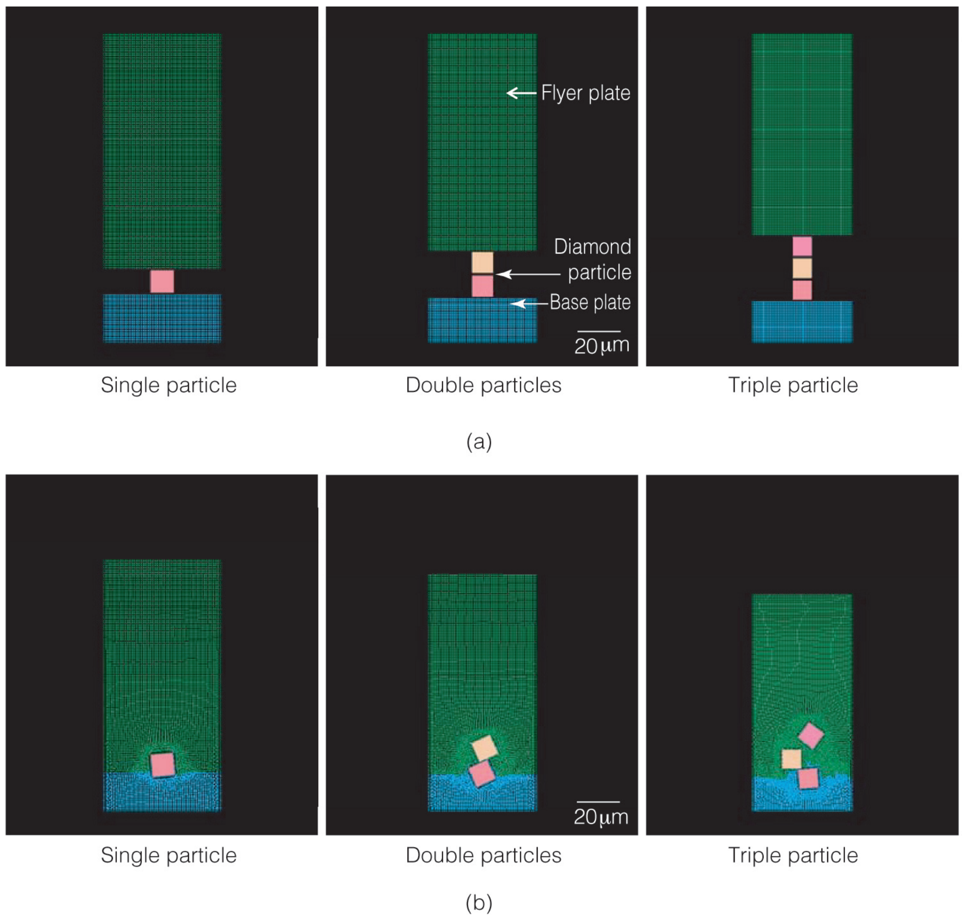


Fig.5 Simplified numerical simulation of penetration of single to triple particle into flyer and base aluminum plate.

simulation model (single, double and triple layered particles) were performed and the results are shown in Fig.5. Since making an exact numerical-analysis model is impossible, a simplified model was used. Diamond particles were placed on base plate at regular intervals, as shown in Fig.5 (a). Since estimating the experiment speed is very difficult; the initial velocity of flyer plate was considered as 500 m/s. For the simulation, A GRUNEISEN equation of state based on Hugoniot was used for the materials employed [9]. We applied GRUNEISEN equation of state and ELASTIC PLASTIC HYDRO for the material parameter of aluminum and diamond. This equation of state with cubic shock velocity-particle velocity defines pressure for compressed material as

$$F = \frac{\rho_0 C^2 \mu \left[1 + \left(1 - \frac{Y_0}{2}\right)\mu - \frac{a}{2}\mu^2\right]}{\left[1 - (S_1 - 1)\mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2}\right]^2} + (Y_0 + a\mu)E$$

C is the intercept of the $v_s - v_p$ curve (v_s: shock wave velocity, v_p: particle velocity), S_1,

Table 3 Parameter of GRUNEISEN equation of state for aluminum and diamond

	c	S_1	S_2	S_3	λ_0	a	E
Aluminum	5340	1.34	0	0	2.0	0	0
Diamond	7810	1.43	0	0	2.0	0	0

S_2 and S_3 are the coefficients of the slope of the $v_s - v_p$ curve, v_0 is the GRUNEISEN gamma, a is the first order volume correction to v_0,

$$\mu = \frac{\rho}{\rho_0} - 1$$

GRUNEISEN coefficients are given in Table 3.

We applied ELASTIC PLASTIC HYDRO for the material parameter of Aluminum and Diamond. This material allows the modeling of an elastic-plastic hydrodynamics material. Material parameter of Aluminum and Diamond for ELASTIC PLASTIC HYDRO are given in table 4. Other condition of numerical simulation is shown in table 5. In a Boundary condition of the model, SPH SYMMETRY PLANE was applied for left, right and bottom face of the model.

From the result of numerical simulation, it is found that large deformation of aluminum was generated by high speed impact between aluminum and particle, and the particle was surrounded by deformed aluminum as shown in Fig.5 (b). In the case of double and triple particles simulation, it can be seen that diamond particles were penetrated into aluminum deeply. Furthermore, the aluminum which behaves as “fluid-like flow” deformation goes to space of around the circumference of the diamond particle. From the results of numerical analysis, it can be concluded that particles tend to penetrate toward the direction of upper aluminum easily and the upper particle was pushed by the below particles. Penetration of the flyer plate can be easily compare with penetration of a base plate. Practically, more diamond powders are stacked and it is considered that the layered particles permeate into deep.

Table 4 Elastic Plastic Hydro parameter of aluminum and diamond

	R0	G	SIGY	EH	PC	FS
Aluminum	2680	25.9E9	0.896E9	0	0	0
Diamond	3191	1200E9	1200E9	0	0	0

R0: Mass density G: Shear modulus SIGY: Yield stress
EH: Plastic hardening modulus PC: Pressure cut off FS: Failure strain for erosion

Table 5 Other condition of numerical simulation

Code	LS-DYNA
Calculation method	SPH
Equation of state	GRUNEISEN
MAT	ELASTIC PLASTIC HYDRO
Mesh size	$0.5 \times 0.5 \times 0.5$ µm
Element	47330 – 47490
Initial condition	INITIAL VELOCITY

4. CONCLUSIONS

A new method of surface modification by high speed collision between metal and micro size diamond proposed and the possibility is investigated The upper surface of aluminum and AZ31 plates was mostly covered by micro size diamond powders and some of the diamond particles were deeply penetrated into the aluminum. Wear characteristic was considerably improved by coated micro size diamond on metal surface. The composite layer on the surface is expected to have some improved properties such as high heat conductivity and will be investigated in future work.

It is found from the results of numerical simulation, the aluminum behaves as "fluid-like flow" deformation goes to space of around the circumference of the diamond particle. Particles tend to penetrate the direction of upper aluminum easily.

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REFERENCES

[1] A.A. Akbari Mousavi, S.T.S. Al-Hassani, Numerical and experimental studies of the mechanism of the wavy interface formations in explosive/impact welding, *Journal of the Mechanics and Physics of Solids*, 2005, 53, 2501–2528.

[2] D.J. Mynors, B. Zhang, Applications and capabilities of explosive forming, *Journal of Materials Processing Technology*, 2002, 125-126, 1-25.

[3] A.G. Mamalis, I.N. Vottea, D.E. Manolakos, On the modelling of the compaction mechanism of shock compacted powders, *Journal of Materials Processing Technology*, 2001, 108, 165-178.

[4] Kakoli Das, Yogendra M. Gupta, Amit Bandyopadhyay, Titanium silicide (Ti5Si3) synthesis under shock loading, *Materials Science and Engineering*, 2006, A 426, 147–156.

[5] K. Hokamoto, M. Fujita, S. Tanaka, T. Kodama, Y. Ujimoto, High-temperature shock consolidation of diamond powders using converging underwater shock wave, *Scripta Materialia*, 1998, 39, 1383-1388.

[6] K. Raghukandan, K. Hokamoto, J. S. Lee, A. Chiba, B. C. Pai , An investigation on underwater shock consolidated carbon fiber reinforced Al composites. *Journal of materials processing technology*, 2003, 134, 329-337.

[7] K. Hokamoto, S. Tanaka, S. Torii, M. Touge, S. Itoh, A New Method for Making Surface Composite Layer by Diamond Particles on an Aluminum Plate Through Underwater Shock Compression, 2005, in Proc. 2. nd. JSME/ASME International Conference. on Materials and Processing (JSME No. 05-203, IMP-. 03, 2005).

[8] Vishal Mehra, Shashank Chaturvedi, High velocity impact of metal sphere on thin metallic plates:A comparative smooth particle hydrodynamics study, *Journal of Computational Physics*. 2006, 212, 318–337.

[9] Marc A. Meyers, Dynamic behavior of materials. Wiley Interscience, *New York*, 1994, 124-151.