Research paper

Surface coating by tungsten carbide particles on a metal substrate by high velocity collision

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Abstract

The surface properties of metal plates were improved using tungsten carbide (WC) powder via a series of experiments, which involved explosions to cause acceleration and flight of metal plates for a high-velocity collision of the metal plates with the WC powder. The flight velocities of the metal plates were calculated by numerical analysis and were consistent with the results obtained by the application of Gurney equations. The combination of fine particle of WC powder with the SUS304 plate resulted in the plastic flow of SUS304 between the WC powder particles that were compressed by impact, forming a film composed of both the materials. The improvement in the wear characteristics of the metal base material was confirmed by wear tests of the films.

Keywords: tungsten carbide, powder coating, explosive, high velocity collision, numerical analysis

1. Introduction

Thermal spraying involves the melting of a powder material that forms a film, and spraying the material on a metal base material at a high speed. Tungsten carbide-cobalt (WC-Co) films formed by thermal spraying plays an important role in reducing the manufacturing cost by extending the life of the surface materials which requires wear resistance[1]. The thermal spraying methods commonly used for WC powder include air plasma spraying, low-pressure plasma spraying, high-velocity oxy-fuel spraying and high-velocity air-fuel spraying[2]. Since the WC powder has a high melting point, an auxiliary binding agent such as cobalt or nickel is always used during spraying[3].

Studies pertaining to metal surface treatments with Nd : YAG lasers have indicated that films composed of powder particles and base materials can be obtained by embedding hard powder particles into the surface of base metal that is in a molten state because of laser irradiation[4)–5)]. However, laser systems are expensive and the processing sizes are limited.

Explosive working is a technology used for material processing which utilises the pressure and heat generated by an explosive. This method does not require any complex and expensive processing systems and there are no limitations on the processing sizes. Representative examples of explosive working include explosive cladding for the manufacture of clad materials[6] and honeycomb structure tube through high-speed impact of metal plates and tubes[7] as well as the instantaneous solidification of sinter-resistant powders such as the WC powder[8]. In our previous study, the underwater shock wave generated by the underwater explosion of explosives was utilised to accelerate an aluminium (Al) plate to high speeds and collide it with diamond powders to form a film composed of diamond and Al on the surface of the Al base material[9]. On the other hand, powder particles were accelerated by an explosive explosion, then. The particles collided to metal substrate, and then deeply penetrated into the substrate[10].

The aim of the present research study is to improve the surface properties of metal surfaces by using WC powder particles. The surface coating of metal plates WC particles was carried out by the acceleration and flight of metal plates to achieve high-speed collisions with the WC powder, with the help of explosives. Experiments were conducted with different types of metal plates, collision velocities of the metal plates and particle sizes of the WC powder, the properties of the recovered driver plates were evaluated through cross-sectional observations and wear tests. Furthermore, the impact velocities were derived by performing numerical analyses.

2. Experimental

In the present work, the WC powder particles were embedded on the surface of the base material plate (driver plate) to form a film or a film composed of the WC powder and the base material. The film was formed by the high-velocity impact of the driver plates on the WC powder. The schematic diagram of the experimental set up is shown in Figure 1. Plates of copper and SUS304 were used as the driver plates in the present study, the explosives were set on the top surface of these plates. The explosives used were PAVEX (detonation velocity: 2,400 m s^{-1}; density: 530 kg m^{-3}) and SEP (detonation velocity: 7,000 m s^{-1}; density: 1,310 kg m^{-3}) of Kayaku Japan Co., Ltd. The No. 6 electric detonator of the same manufacturer was used to detonate the explosives. The coarse particle (75 to 150 μm) and the fine particle (7.5 to 12 μm) grades of the WC powder manufactured by Japan New Materials were used. The WC powder was placed on top of base plates which were positioned at distance of 3 mm from the driver plate. During the explosion, the driver plate collided with the WC powder at high velocity. The base plate also served the purpose of reducing the damages sustained by the anvil. The scanning electron microscope (SEM) images of the WC powder particles are shown in Figure 2. The WC powder with coarse particles have angular shapes, while that with the fine particles are round shaped. The details of the experimental conditions are described in Table 1. PAVEX is a powder-type explosive and the amount of fill used was twice the mass of the driver plate. We used SEP, a plastic explosive, in the tabular form.

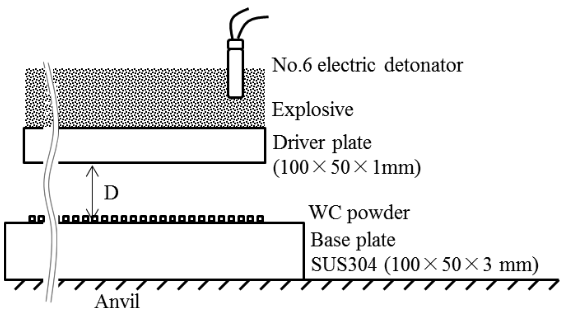

Figure 1 Schematic diagram of the experimental set up.

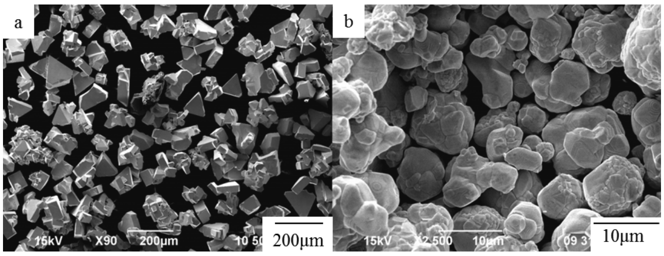

Figure 2 SEM image of WC powder particles (a: coarse particle, 75–150μm, b: fine particle 7.5–12μm).

3. Results and discussion

3.1 Collision velocity

It is considered that the collision velocity of the driver plate is one of the most important parameter. Since the explosive is initiated from one spot at the area of detonator, the driver plate should be three-dimensionally deformed. Although three-dimensional analysis is necessary to predict an accurate collision velocity of the driver plate, in this study, the approximate collision velocity was estimated by the Gurney equation[11] and two-dimensional analyses[12] and was evaluated validity of the stands off in the case using the SEP explosive. The terminal velocity of the driver plate can be calculated using the Gurney equationsas shown in Equation (1).

Table 1 Experimental conditions.

No.	Driver plate	Explosive		WC powder	
		Type	Charging mass [g]	Diameter [μm]	Weight [g m^{-2}]
1	Copper	PAVEX	87.5	75–150	0.088
2	JIS SUS304	PAVEX	72.5	75–150	0.089
3	Copper	SEP	36.0	75–150	0.091
4	JIS SUS304	SEP	36.0	75–150	0.088
5	Copper	PAVEX	36.0	7.5–12	0.150
6	JIS SUS304	SEP	36.0	7.5–12	0.180

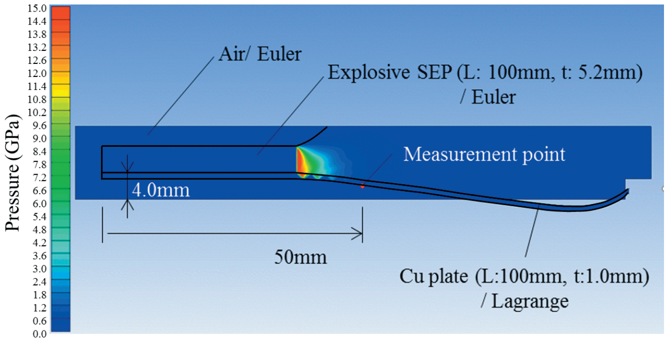

Figure 3 2-dimensional analysis model and flight process by explosive detonation.

$$V=\sqrt{2E}\left[\frac{\left(1-2\frac{M}{C}\right)^3+1}{6\left(1+\frac{M}{C}\right)}+\frac{M}{C}\right]^{-1/2} \tag{1}$$

Where M (Cu : 44.70×10^{-3} kg, SUS304 : 39.65×10^{-3} kg) and C (34.06×10^{-3} kg) is mass of driver plate and explosive. Gurney energy E is unique to each explosive and a value of 2.16 MJ kg^{-1} was used in this work[13]. The terminal velocities V of the copper and the SUS304 plates in the experiments that involved the use of the SEP explosive were calculated as 947 and 1,029 m s^{-1}, respectively.

The two-dimensional analysis model and the flight process using a commercial analysis software (ANSYS AUTODYN) are described in Figure 3. The flight velocity of the driver plate at the acceleration distance of 4 mm was derived using the Euler equation for the explosives and air, while the Lagrangiane coordinate system was used for the driver plate. The analysis results that represent the flight velocity and the acceleration distance at one point on the lower side of the driver plate are shown in Figure 4. The flight velocity of copper and SUS 304 derived by numerical analysis saturated at the acceleration distance of 4 mm and the terminal velocity was 987 and 1058 m s^{-1} respectively. This result is consistent with the terminal velocity calculated using the Gurney equations described above. Furthermore, the collision velocity at the acceleration distance of 3 mm was 960 and 1040 m s^{-1} respectively, revealing that the driver plate reached the terminal velocity at the acceleration distance of 3 mm.

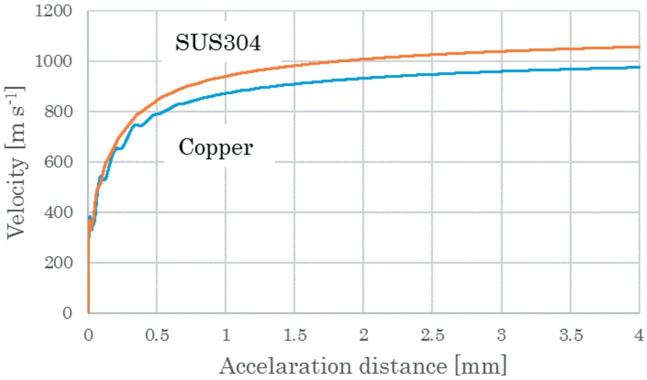

Figure 4 Analysis result of driver plate velocity at each acceleration distance.

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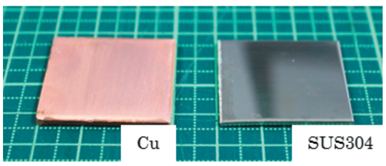
3.2 Sample observations

The external appearance and the surface images of the recovered driver plates are shown in Figure 5. The colour of the base material was verified from the photographs of the samples obtained from the experiments in No. 1 to 4 involving the use of the coarse particle WC powder. However, such verification was not possible for the experiments in No. 5 and 6 involving the use of the fine particle WC powder, since large amounts of the WC powder particles accumulated on the surface. The SEM images of the samples from experiment No. 2 indicate that relatively large WC powder particles remained on the surface of the base material, while in the case of experiment No. 4, the WC powder particles were finely fractured. The results indicated that the collision velocity of the driver plate in the case of the PAVEX explosion was lower than the case of the SEP explosion. The fine particle WC powder was found to be unevenly accumulated in



Original driver plate

Combination of materials

No.	Drive plate	Explosive	WC diameter [μm]
1	Cu	PAVEX	75-150
2	SUS304	PAVEX	75-150
3	Cu	SEP	75-150
4	SUS304	SEP	75-150
5	Cu	PAVEX	7.5-12
6	SUS304	SEP	7.5-12

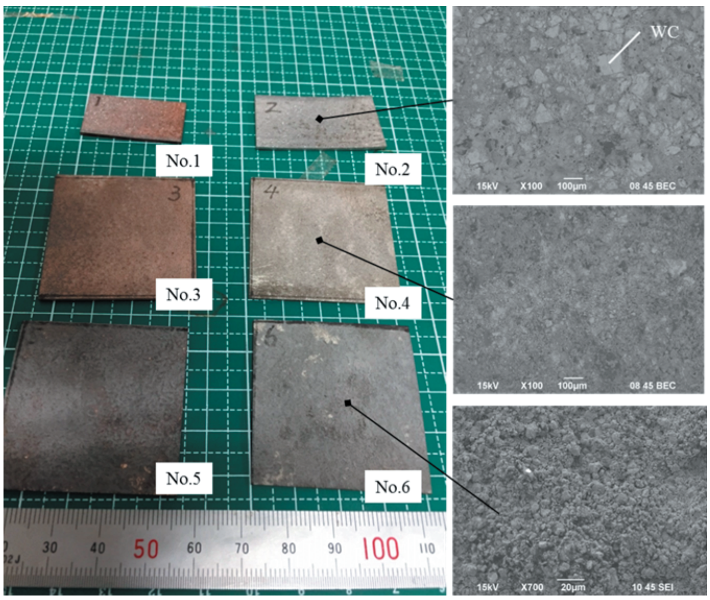


Figure 5 External appearance and the surface SEM images of the recovered driver plates.

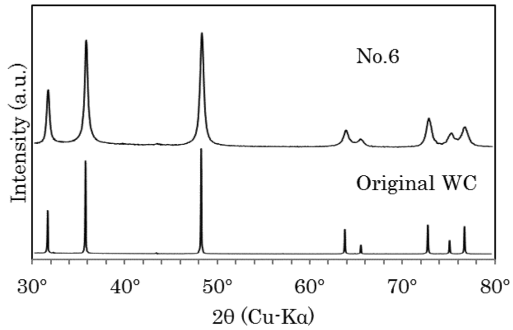


Figure 6 XRD pattern (Cu Kα) taken from upper surface of No.6 and original WC powder.

layers in the samples obtained from experiment No. 6.

Figure 6 shows the X-ray diffraction pattern (Cu-Kα) for the sample taken from the upper surface of No.6, and the Figure 6 shows that width of the WC peaks became larger compared with un-shocked original WC powder. This indicates that WC particles were more strained as suggested for explosively consolidated diamond powders[14].

The cross-sectional microscopic images of the recovered driver plates are shown in Figure 7. In experiment No.4, the coarse WC particles (75 to 150 μm) were used. The particles were crashed by the collision and the crashed particles were embedded in the SUS304 base material. The black arrows show cracks in the embedded particles, a part of drop out due to the fracture was confirmed. The samples from experiment No. 1 to 3 showed similar results. It was confirmed that large amounts of the WC powder particles were accumulated on the No.5 surface (Figure 5). On the other hand, only small amounts of the particles were confirmed in Figure 7 (No.5) indicating the cross section after the polishing. It means that the WC particles were dropped off from the surface in the polishing process.

In experiment No. 6, the fine WC particles were piled up on the surface of the SUS304 plate as observed from a part of the sample (Figure 7, No. 6 (a)). The SEM images displaying the magnified views of the locations where the WC powder particles were piled up, confirmed the existence of cracks inside the relatively large WC powder particles as shown by white arrows, while the plastic flow of the base material due to high pressure was confirmed by the images of the WC powder particles that were crushed and fractured (Figure 7, No. 6 (b)). Base metal material is deformed as "fluid-like flow", when the base material collides with powder particle at high velocity[9]. It is believed that the WC powder particles fracturing during the compression process and the plastic flow of the base material between the particles have resulted in the film formation. This is because some of the WC powder particles that did not fracture were embedded in the base material, while some other particles that were fractured accumulated in layers. These results indicate the potential for the development of a technology for the film formation of WC powder without the use of any binding agent. Furthermore, since the strength of the WC powder particles depends on the particle diameter[15], it is believed that using finer particles would make it more difficult to crush the particles and result in stronger films.

3.3 Wear tests

A series of wear tests were performed in order to investigate the ability of the metal base material to retain the WC powder particles. A summary of the wear test is shown in Figure 8. The recovered driver plates were placed on top of a turn table and a load of 0.2 kg was applied using a stainless-steel ball indenter. The indenter was fixed at a distance of 2 mm from the axis of rotation

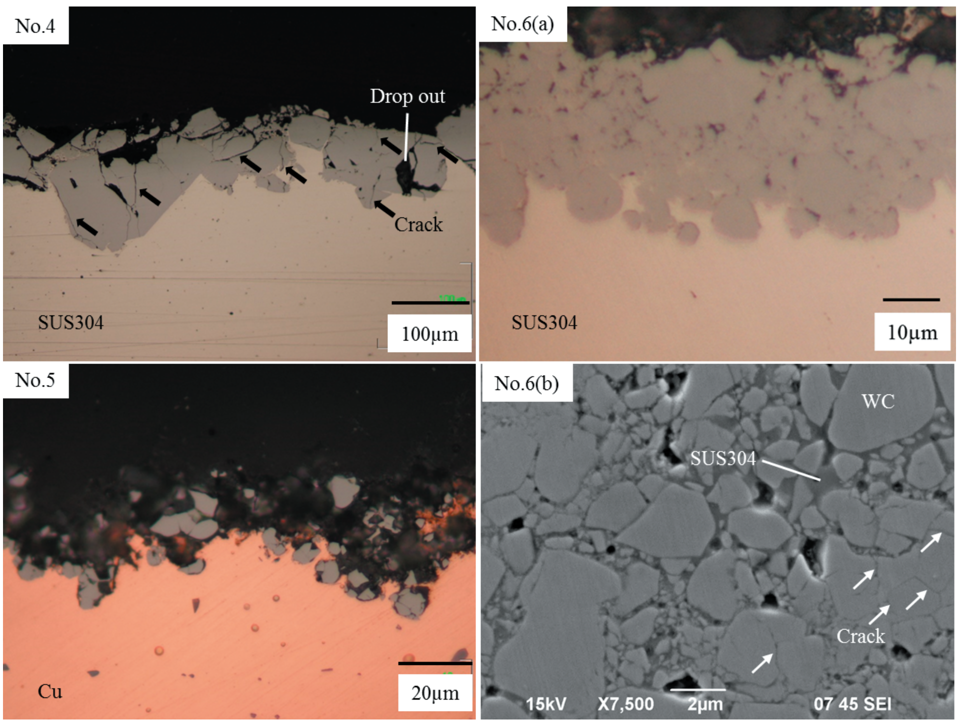


Figure 7 Cross-sectional optical (No.4–6) and SEM (No.6) image of recovered driver plate.

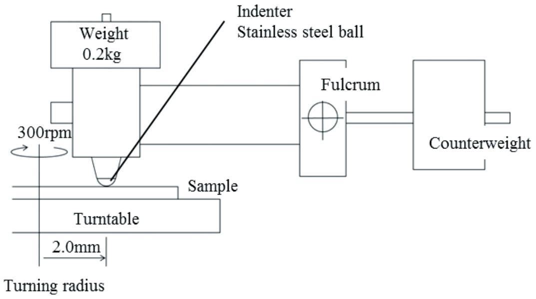


Figure 8 Schematic diagram of wear test apparatus.

Table 2 Wear test results.

Sample	Test time [ks]	Mass change [mg]
Cu*	1.8	−1.0
	6.0	−9.0
SUS304*	6.0	−0.9
No.1	1.8	−0.2
	6.0	−0.8
No.2	6.0	−0.1
No.3	6.0	−0.9
No.4	6.0	−0.1
No.5	1.8	−5.5
No.6	6.0	−0.9
	9.0	−0.9

*Untreated metal plate

and the rotational velocity was set to 300 rpm. The test time was set to 1.8, 6.0 and 9.0 ks, and the mass decrement (wear amount) of the sample was measured. The wear amount corresponds to peeling-off of the particles by the wear test, therefore the adhesive strength between the metal base material and the WC particle can be shown by the wear amount. Untreated copper and SUS304 plates were also evaluated with same procedure in order to confirm the improving wear resistance of the recovered driver plates. The results of the wear tests are shown in Table 2. The WC powder particles that were embedded on the surface of the base material were firmly retained, since the wear amount of recovered No. 1 to 4 samples was relatively small compared with the untreated copper and SUS304 samples. The wear amount of No.5 was larger than the amount of the untreated copper plate. The large accumulation of the fine WC particles on the surface has been confirmed by the upper surface photographs. It is considered that the fine WC particles were compressed and accumulated without physically bonding between the particles. Therefore, they were shaved off easily, and then the wear amount become large. Also in experiment No. 6, the large accumulation of the WC particles on the surface has been confirmed by the upper surface photographs. Although the wear amount after 6.0 ks for the sample obtained from experiment No. 6 was same as that from untreated SUS304 plate, there was no change in the amount after 9.0 ks. This suggests that the firm coating film with high adhesion to a base material was formed. But, the fine WC powder particles that accumulated on the film were shaved off, like No.5 sample.

4. Conclusion

An experiment in which explosives were used to accelerate and fly metal plates to impact powder particles of WC, was carried out in order to improve the metal surfaces by using the WC powder.

The approximate flight velocities of the metal plates in the case using SEP were calculated by numerical analysis, and the results were consistent with those obtained by the application of Gurney equations, which led to the clarification of the collision velocity at the acceleration distance of 3 mm.

A part of the WC powder particles was embedded in the base material in the experiment that involved the use of the coarse particle WC powder. The embedded WC powder particles were firmly retained by the base material, as confirmed by the wear tests. However, a film consisting of the WC particles and the metal base material could not be formed using the coarse WC particles.

The combination of fine particle WC powder particles with the SUS304 plate (No.6) resulted in the plastic flow of the SUS304 base material between the WC powder particles that were compressed, and formed a film composed of both the materials. The wear tests of the No.6 sample indicated that the firm coating film with large adhesion to a base material was formed.

The presented work demonstrates the potential for the development of a technology for the formation of films of WC powder without the use of binding agents.

Acknowledgment

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