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Friction Behavior of High Velocity Oxygen Fuel (HVOF) Thermal Spray Coating Layer of Nano WC-Co Powder

T. Y. Cho[a*], J. H. Yoon[a], K. S. Kim[a], W. Fang[a], Y. K. Joo[a], K. O. Song[a], S. J. Youn[b], S. Y. Hwang[c], H. G. Chun[d]

[a]*School of Nano Advanced Materials Engineering, Changwon National University, Changwon 641-773, Korea*
[b]*Sermatech Korea Co., Ltd., Changwon 641-120, Korea*
[c]*Research Institute of Industrial Science & Technology, Pohang 790-330, Korea*
[d]*School of Materials Science & Engineering, University of Ulsan, Ulsan 680-741, Korea*

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Abstract

High Velocity Oxygen Fuel (HVOF) thermal spray coating of nano size WC-Co powder (nWC-Co) has been studied as one of the most promising candidate for the possible replacement of the traditional hard plating in some area which causes environmental and health problems. nWC-Co powder was coated on Inconel 718 substrates by HVOF technique. The optimal coating process obtained from the best surface properties such as hardness and porosity is the process of oxygen flow rate (FR) 38 FMR, hydrogen FR 57 FMR and feed rate 35 g/min at spray distance 6 inch for both surface temperature 25°C and 500°C. In coating process a small portion of hard WC decomposes to less hard W_2C, W and C at the temperature higher than its decomposition temperature 1,250°C resulting in hardness decrease and porosity increase. Friction coefficient increases with increasing coating surface temperature from 0.55-0.64 at 25°C to 0.65-0.76 at 500°C due to the increase of adhesion between coating and counter sliding surface. Hardness of nWC-Co is higher or comparable to those of other hard coatings, such as Al_2O_3, Cr, Cr_2O_3 and HVOF Tribaloy 400 (T400). This shows that nWC-Co is recommendable for durability improvement coating on machine components such as high speed spindle.

Keywords : HVOF, nWC-Co, Thermal spraying, Optimal coating process, Friction coefficients

1. Introduction

Electrolytic hard chrome (EHC) plating has been widely used in commercial production over 60 years both for surface hard coatings and re-build of worn and corroded components[1)]. EHC plating baths emit Cr^{6+} ion mist known as carcinogen causing lung cancer. HVOF thermal spray coating technique is the promising candidate for the replacement of EHC and other traditional electro plating which causes severe health and environmental problems[1-6)]. HVOF thermal spray coating technique can be used to deposit both metal alloys and ceramics/metal coating. The coatings are dense, thick and highly adherent to the base materials[1)]. As the application of technology grew, it began to be applied to a wide range of other types of coatings including a variety of aircraft components and outside the aircraft industry. Although HVOF coating has been replaced a wide number of traditional coatings, their qualification as a completely acceptable replacement for the traditional coating has not yet been sufficiently demonstrated. Therefore, intense research is required for better application. For HVOF hard coatings, Co alloys and hard WC-metals powders are intensively investigated. In this study, hard nWC-Co powder is coated on the Inconel 718 substrates by HVOF thermal spraying processes designed by Taguchi program for four spray parameters with three levels for the application of hard WC-Co coating on high speed spindle. The optimal coating process is obtained from the best surface properties such as hardness and porosity. Phase changes and decomposi-

*Corresponding author. E-mail : tycho@changwon.ac.kr

tion reactions of WC-Co powders during the coating precess have been investigated for the study of the effects of spray parameters on coating properties. The dependence of surface properties on spray parameters has been investigated for the improvement of coating quality. The dependence of friction coefficient (FC) on spray parameters and coating surface temperature have been investigated for the study of temperature effect on FC and application to machine components. Hardness and FC of nWC-Co are compared with other traditional coatings such as Al_2O_3, Cr, Cr_2O_3 and HVOF Tribaloy 400 (T400) for the study of the durability improvement coating of sliding surface of machine components.

2. Experimental Work

2.1 Preparation of Coating

A commercially available m & nWC-Co (12 wt% Co), Al_2O_3, Cr_2O_3 and T400 are coated on Inconel 718 substrates by JK3500 thermal spraying equipment, and Cr is coated by electrolytic plating. Substrates are pre-cleaned in acetone for 5 minutes and then blast cleaned by 60 mesh aluminium oxides. Coatings are prepared by 9 different processes designed by Taguchi experimental program for 4 spray parameters with 3 levels as shown in Table 1[7-10]. Spray gun speed is 3 mm/s and Argon gas is used as a powder carrier gas. Coating is cooled in the air.

2.2 Properties of Coating and Friction Test of the Coating

Microstructure and phase are investigated by SEM and XRD. The surface hardness is measured by micro vickers hardness tester.

Table 1. Coating processes

Process	Spray parameters			
	O_2 flow rate (FMR)	H_2 flow rate (FMR)	Spray distance (inch)	Feed rate (g/min)
1	30	53	6	25
2	30	57	7	30
3	30	61	8	35
4	34	53	7	35
5	34	57	8	25
6	34	61	6	30
7	38	53	8	30
8	38	57	6	35
9	38	61	7	25

1 FMR = 12 scfh

Hardness is the average value of 9 measurements at the center of cross section of the coating layer. Porosity is the average value of 5 data obtained by analyzing the images photographed by optical microscope. Friction coefficients of coating are investigated by the reciprocating slide tester (TE 77 AUTO, Flint & Partners). Coatings are slided by the SUS 304 counter sliding ball of 9.53 mm diameter and hardness of 227 Hv without using any lubricants. The reciprocating slide distance, frequency, speed, load and sliding time are 2.3 mm, 35 Hz, 0.161 m/s, 10 N and 4 minutes respectively. Sliding test is carried out at room temperature and at an elevated temperature of 500°C for the study of the temperature effects on friction behaviors.

3. Results and Discussion

3.1 Formation of Coatings

As shown in Fig. 1, nWC-Co powder prepared by spray drying method has the shapes of broken piece of various sizes. Particles are mixture of WC and Co phases. As shown in Fig. 2, XRD pattern of nWC-Co powder shows crystalline WC and Co. Particles of various sizes, shapes and masses are injected into the high temperature flame of up to 3500°C formed

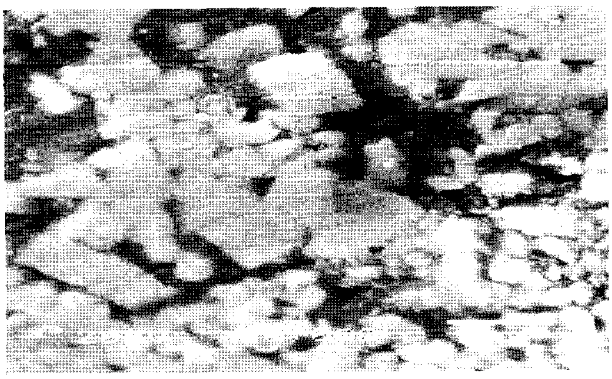

Fig. 1. SEM micrograph of nWC-Co powder.

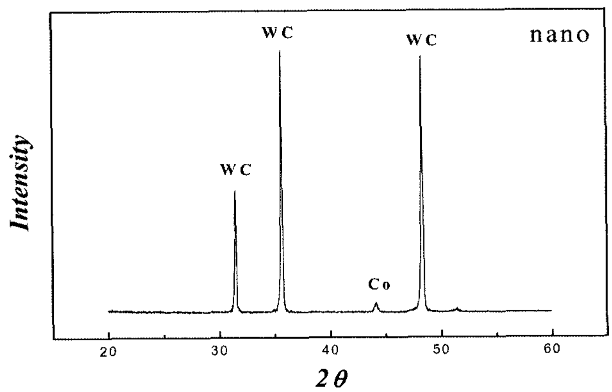

Fig. 2. XRD pattern of nWC-Co powder.

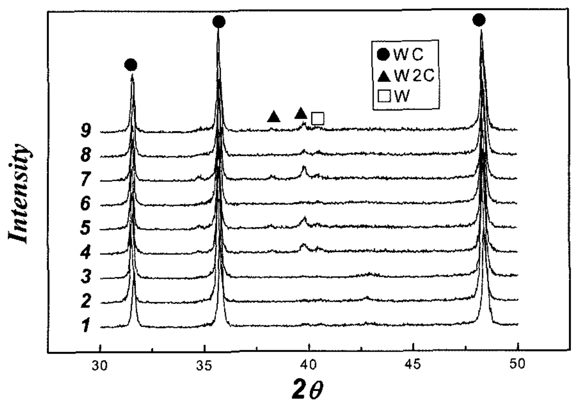

Fig. 3. XRD pattern of nWC-Co coating.

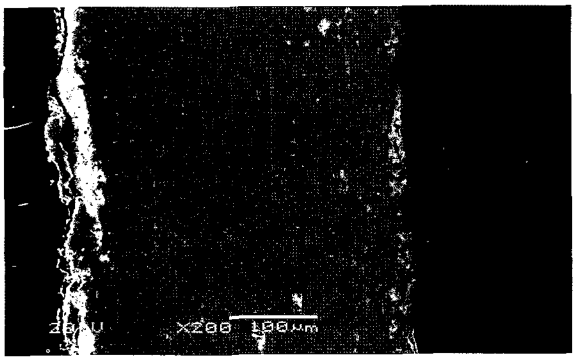

Fig. 4. Cross section of nWC-Co coating.

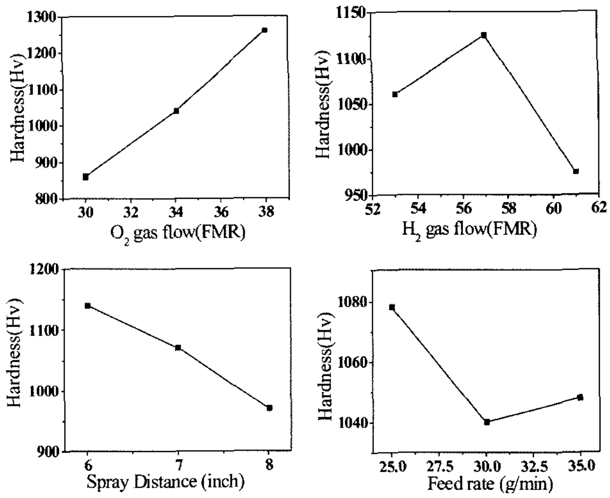

Fig. 5. Hardness vs spray parameters.

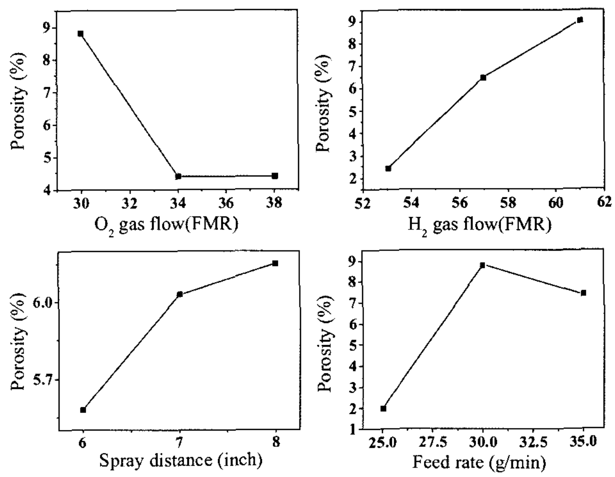

Fig. 6. Porosity vs spray parameters.

by the combustion of fuel gas hydrogen and oxygen[1,4,7]. During the short flight time of 0.1-1 ms, a small portion of WC pieces decomposes to W_2C, W and C as seen in XRD pattern in Fig. 3, and melts or partially melts. The Co phase are molten, partially molten or soften[1,4,7]. These various splats impact on the coating surface with supersonic velocity of up to 1,000 m/s[1,4,10]. Upon impact a bond forms with the surface, with subsequent splats causing thickness build up and forming a laminar structure. The hot splats undergo quenching at very high quenching rates, typically in excess of 10^6 K/s[1,2,4,7,10]. The splats form fine grained coatings of 300-350 µm thickness with good adhesion to substrate as shown in Fig. 4.

As shown in Fig. 3, XRD pattern of coating shows small amount of W_2C and W phases formed by the decomposition of WC during the short time of flight in the hot flame. According to phase diagram[11] dWC decomposes to βW_2C, W and graphite at the temperature above 1,250°C. And βW_2C melts and decomposes to W and graphite at temperature above 2,785 ± 10°C. These less hard W_2C, W and graphite phases reduce the surface hardness.

3.2 Surface Properties of nWC-Co Coating

Surface hardness depends on the spray parameters as shown in Fig. 5. Hardness 940-1,200 Hv of nWC-Co coating is twice higher than the hardness about 600 Hv of T800 coating prepared by the same equipment[5,6,8,10]. As shown in Fig. 5, hardness increases with increasing oxygen flow rate, since the excess oxygen reagent reacts with less hard graphite produced by the WC decomposition, and removes it as carbon oxide gas products. Hardness decreases with increasing spray distance, since the exposing time of WC in the flame increases, and it causes more decomposition of hard WC to less hard W_2C. As shown in Fig. 6, porosity 2.5-9.0% is more than ten times porous compared to 0.010-0.035% of T800 coating prepared by the same equipment[5,6,8,10]. A small portion of WC pieces decomposes to W_2C, W and graphite at higher temperature above the decomposition temperature 1,250°C[11]. The decomposed graphite reacts with the excess oxygen and evolves carbon oxide gasses causing porous coating.

3.3 Friction behavior of the Coating

As shown in Fig. 7, The optimal coating process for the friction resistant coating is the process of oxygen FR 38 FMR, hydrogen FR 57 FMR, feed rate 35 g/min and spray distance 6 inch for both 25°C and 500°C. The friction coefficient increases with increasing the surface temperature from 0.55-0.64 at 25°C to 0.65-0.76 at 500°C. This is the reverse phenomenon to Co-alloy T800[5-9,11]. Metallic Co matrix surrounds and bonds WC pieces in the coating. At the beginning of the sliding, metallic Co plays the major role in the wear and friction. The soft (550-630 Hv) and low melting (1,500°C) and reactive metallic Co easily oxidize at high temperature. The brittle Co oxides, such as CoO and Co_3O_4 phases are easily abraded by the oxidation and abrasive wear mechanisms. The abraded oxides are molten, partially molten or softened, and they play roles as solid and liquid lubricants reducing friction coefficient at high temperature[5-10]. Soon, the hard (940-1,200 Hv), high melting (2,970°C) and stable WC pieces start to play major role in the sliding. Hard WC pieces do not easily form brittle oxides, and hard WC surface does not easily attrit wear debris which function as solid and liquid lubricants. The true contact area of the asperities is smaller than the apparent area (about 0.01% of apparent area), the asperities are under very high local pressure of up to 10^5 times of the test load, The asperities of two contact surfaces are locally cold-welded by the intermolecular and interatomic bond[12]. According to phase diagram[11], 30-50 wt% of both Cr and Fe of the sliding ball are soluble in aCo of WC-Co coating near 500°C and tend to induce solution welding, increasing adhesion and FC at high surface temperature as shown in Fig. 7[11,12].

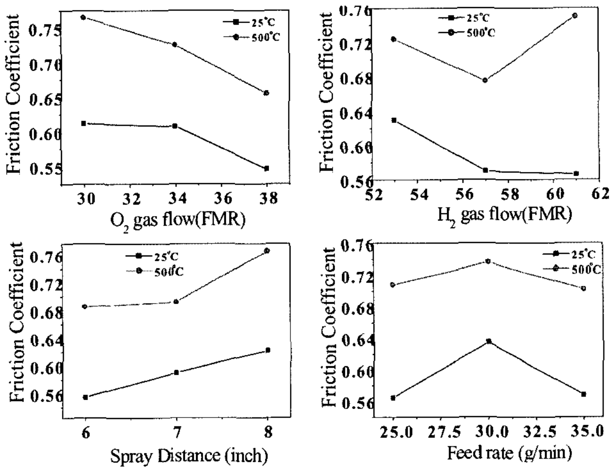

Fig. 7. Friction coefficient of nWC-Co coatings vs spray parameters at 25°C and 500°C.

3.4 Comparison of nWC-Co with other Hard Coatings

As seen in Fig. 8 the surface hardness of 9 nWC-Co samples is in the range of 500-1,300 Hv depending on the coating processes. The coating of highest hardness 1,300 Hv is prepared by 8th process of Table 1; oxygen FR 38 FMR, hydrogen FR 57 FMR, feed rate 35 g/min and spray distance 6 inch. Hardness is strongly dependent on coating processes, as shown in Fig. 8, hardness of nWC-Co is comparable to Cr_2O_3 plating, much higher than those of the coatings of Cr, Al_2O_3, T400, and lower than the coating of mWC-Co. As shown in Fig. 9, the FC of nWC-Co coating is comparable to other coatings both at 25°C and 500°C. It increases with increasing surface temperature from 0.45-0.68 at 25°C to 0.58-0.82 at

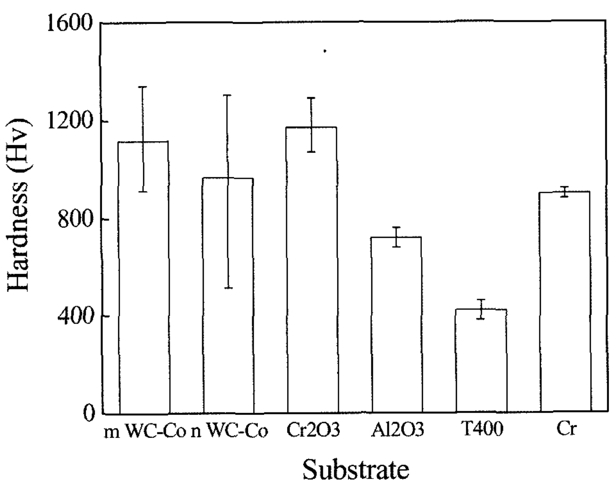

Fig. 8. Hardness of coatings: mWC-Co, nWC-Co, Cr_2O_3, Al_2O_3, T400 and Cr.

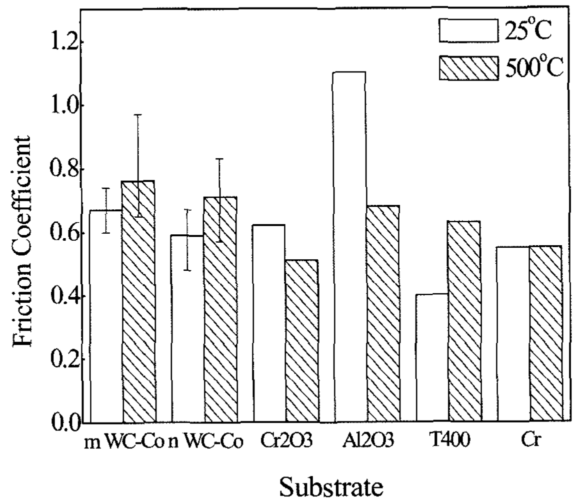

Fig. 9. Friction coefficients of mWC-Co, nWC-Co, Cr_2O_3, Al_2O_3, T400 and Cr coating at 25°C and 500°C.

500°C, depending strongly on the coating process. As discussed in 3-2, at the beginning of the sliding low melting Co, which surrounds WC pieces, plays major role decreasing friction coefficients as increasing the surface temperature due to the solid and liquid lubrication by the abraded debris[7-11,13].

The stable and hard ceramic WC pieces play major role increasing friction coefficients as increasing surface temperature, since the adhesive strength between the coating and sliding surface is stronger at higher temperature.

4. Conclusions

1. The optimal coating process for the friction resistant coating is the process of oxygen flow rate 38 FMR, hydrogen flow rate 57 FMR, feed rate 35 g/min and spray distance 6 inch for both 25°C and 500°C.

2. A small portion of WC decomposes to less hard W_2C, W and graphite during the spraying.

3. Friction coefficient increases with increasing sliding surface temperature.

4. Hardness of nWC-Co coating is strongly dependent on spraying parameters. It is comparable to EHC, higher than other coatings and lower than mWCo coating.

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References

1. B. D. Sartwell, R. Kestler, K. O. Legg, W. Assink, A. Nardi, J. Schell, NRL Report No. XYZ, Naval Research Laboratory, Washington DC 20375 (2003) 1-5.
2. B. D. Sartwell, K. O. Legg, J. Schell, J. Sauer, P. Natishan, D. Dull, J. Falkowski, P. Beretz, J. Devereaux, C. Edwards, D. Parker, Naval Research Laboratory Report Number NRL/MR/6170-04-8762, (2004) 1-30.
3. B. D. Sartwell, K. Legg, B. Bodger, HVOF Thermal Spray Coatings as an Alternative to Hard Chrome Plating on Military & Commercial Aircraft, AESF/EPA Conference for Environmental Excellence, 231 (1999) 1-20.
4. J. R. Davis, Handbook of Thermal Spray Technology, ASM International, USA (2004) 1-30.
5. T. Y. Cho, J. H. Yoon, K. S. Kim, N. K. Baek, S. Y Hwang, S. J. Youn, H. G Chun, HVOF Coating of Co-alloy T800 for the Improvement of the Performance and Durability of Military Hardware Components, 15th Aero Technology Symposium, Logistics Command ROKAF, September 15, 2006.
6. T. Y. Cho, J. H. Yoon, K .S. Kim, S. J. Youn, N. K. Baek, B. C. Park, S. Y. Hwang, H. G. Chun, Kor. Soc., Machine Tool Engineers, 15(6) (2006) 32-37.
7. K. S. Kim, N. K. Baek, J. H. Yoon, T. Y. Cho, S. J. Youn, S. Y. Oh, S. Y. Hwang, H. G Chun, J. Kor. Surface Engineering, 39(4) (2006) 179-189.
8. T. Y. Cho, J. H. Yoon, K. S, Kim, S. J. Youn, N. K. Baek, H. G. Chun, S. Y. Hwang, J. Kor. Inst., Surface Engineering, 39(5) (1966) 240-244.
9. B. Hwang, J. Ahn, S. Lee, Mater. Trans., 33A (2002) 2933.
10. T. Y. Cho, J. H. Yoon, K. S. Kim, B. G. Park, S. J. Youn, N. K. Baek, H. G. Chun, J. Korean Crystal Grow and Crystal Technology, 16(3) (2006) 121-126.
11. T. G. Massalski, *et al.*, Binary Alloy Phase Diagram, Am. Soc. for Metals 1 (1986) 600.
12. A. W. Adamson, Physical Chemistry of Surfaces, 4th Ed. John Wiley and Sons (1982) 404-450.