Influence of Powder Size and Strength on HVOF Spraying - Mapping the Onset of Spitting

颗粒尺寸和强度对超音速火焰喷涂的影响 ——映射枪管堵塞/大熔滴的临界点

T. Itsukaichi and S. Osawa

Fujimi Incorporated, Kakamigahara, Gifu, Japan

R. Ahmed

Heriot-Watt University, School of EPS, Riccarton, Edinburgh, EH14 4AS, United Kingdom

Abstract

In the case of thermal spraying of cermet powders using HVOF with longer barrel, such as a JP-5000 and a Diamond Jet 2700, spitting and clogging troubles tend to be brought about on the inner wall of the barrel. This phenomenon comes from the existence of fine particles (in spray powders) which tend to fully melt through barrel. This investigation has been carried out to realize the influence of powder particle strength and particle size distribution of agglomerated and sintered Cr_3C_2-25%NiCr powders during HVOF spraying. It is found that the finer and weaker the powder particles, the higher the deposit efficiency. However, the finer and weaker the powder particles, the easier is the onset of spitting and clogging phenomena. On the contrary, it is found that the coarser and stronger the powder particles, the lower the deposit efficiency with less spitting and clogging phenomena. Finally optimum powder particle strength and particle size distribution of Cr_3C_2-25%NiCr powders have been found in this study using a JP-5000 system.

Introduction

The aim of this investigation, which is the first of its kind in published literature, was to ascertain the HVOF process conditions which will prohibit the onset of spitting in cermet coatings. Spitting is a major problem leading to poor coating quality and financial losses due to downtime and maintenance costs. Figure 1 shows typical schematic of some of the problems associated with spitting i.e. barrel clogging and flaked sediments within the coating microstructure. The term spitting in this article is thus collectively used to define both the onset of barrel clogging and the introduction of flaked sediments within the coating microstructure.

Industrial Context of the Problem

The economics of thermal spraying job shop rely on preventive maintenance and acceptable coating quality to meet the standards defined by the aerospace and process industries. One of the major challenges is to balance the deposit efficiency while adapting a preventive maintenance approach. Hence the phenomenon of spitting is crucial, a thorough understanding of which can help minimize its effects on job shop performance. The problem of spitting and clogging is not unique to thermal spray industry and similar problems are associated with the spray industry in general e.g. Foley et al. [1] has indicated that identification of underlying problem associated with clogging and caking of spray gun can be difficult. However, changes such as flow rate variations, spray drop size increases, spray impact transition and spray pattern alignment are some of the earlier signs which could be used to identify the problem. Nevertheless, an understanding of the interdependence among the spray process, process parameters and powder morphology can help minimize the frequency, and also identify the root cause of such problems.

The Process of Spitting

Spitting originates from two main sources i.e. powder particle size and particle strength. The former is due to the fact that fine powders overheat and fuse to clog the barrel wall, whereas the significance of particle strength lies in the fact that poor strength particles burst in the flame, resulting in fine powder particles, which eventually lead to spitting.

Spitting vs. Coating Process and Powder Manufacturing Route

One of the practical ways to avoid spitting is to eliminate barrel from the spraying process. In this context, it is not surprising that Plasma Spray coatings, where powder is fed externally into the plasma arc, spitting problem is eliminated. However even in plasma spraying where powder is fed internally, spitting problem can occur. Similarly, recent advances such as the use of HVOF Theta Gun [2], which utilizes air stream instead of barrel to propel the particles, can avoid the onset of spitting. However, conventional HVOF

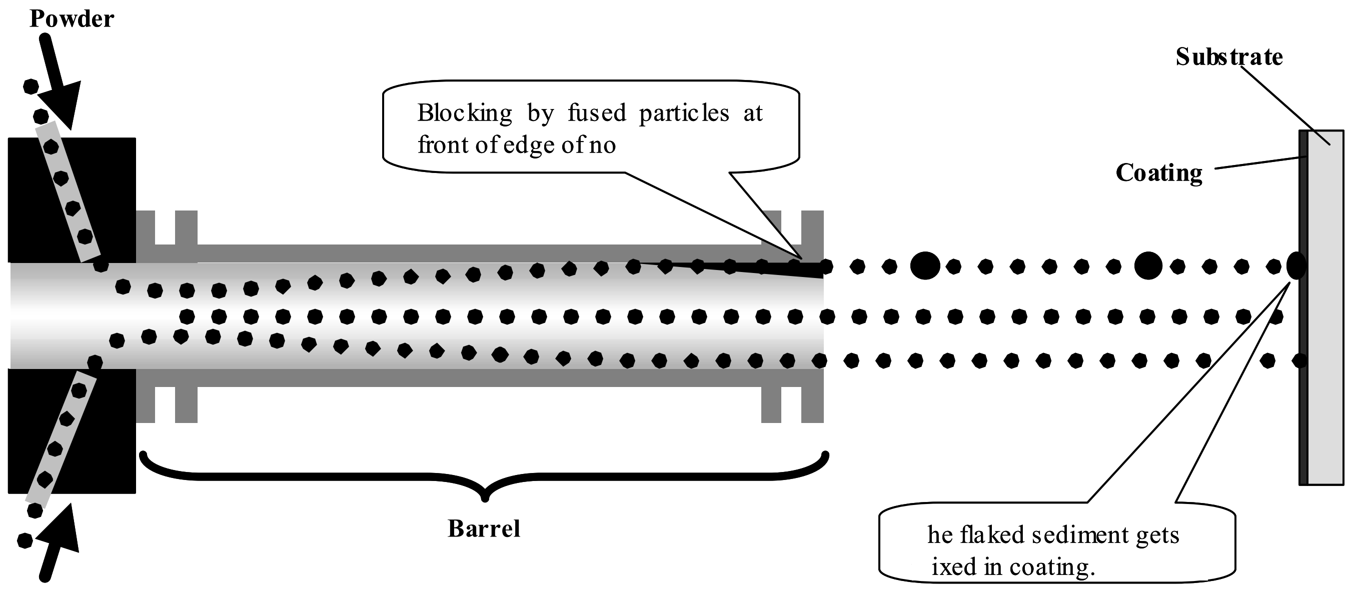

Figure 1: Schematic of typical spitting during HVOF spraying with barrel.

Table 1: Typical industrial consumption of cermet powders in Japan.

Powder Manufacturing Route	Particle Strength	Spitting Problem	Deposit Efficiency	Industrial Usage / Year
Fused and Crushed	Very High	Very Rare	Low	3%
Sintered and Crushed	Medium - High	Rare	Low - Medium	9%
Agglomerated and Sintered	Low - High	Rare - Frequent	Low - High	81%
Clad (Plating)	-	Rare - Frequent	Low	5%
Blend	-	Rare - Frequent	Low	2%

systems rely on the use of barrel to accelerate the powder particles, and thus normally suffer from spitting. Hence in situations where conventional HVOF process is desirable, the appropriate selection of powder manufacturing route and typical particle size distribution becomes important to avoid spitting.

In terms of the various methods of powder manufacture for cermet coatings e.g. Fused and Crushed, Sintered and Crushed, Agglomerated and Sintered, Plating (Clad) and Blending; agglomerated and sintered powders represent the work horse of thermal spray industry. Table 1 shows typical industrial usage of the common cermet powder manufacturing routes in Japanese thermal spray industry [3, 4, 5]. This table also highlights typical particle strength and thus their spitting potential due to bursting of powder particles. It can be appreciated from Table 1 that agglomerated and sintered powders, by far represent the most commonly used powder manufacturing route for cermet powder production. In addition, the powders produced by this process normally have a high spray deposit efficiency and a broad range of particle strengths. It is for these reasons that agglomerated and sintered powders were considered for this study.

Experimental Procedure

Powder Manufacture

Several Cr_3C_2-25mass%NiCr powders with various strengths and fine particle proportion were made by the agglomerated and sintered processing route. The strength of these particles was controlled by changing the sintering conditions, especially sintering temperature, whereas the content of the fine particle proportion was varied by appropriate crushing, sieving and air classification. Nominal size distribution of these powders was 15-45μm, which was typical of some of the commercially available powders.

Deposition Conditions

A JP-5000 HVOF system was used to deposit coatings on steel substrate (mild steel). This process was selected because of its commercial attractiveness in terms of particle velocity and temperature. Table 2 shows the spray deposition conditions adapted for this investigation which were typical of the recommended parameters for this spraying process. As the nominal particle size was constant for all the powders used in this study, similar spray deposition conditions were adapted for all coatings, so that their evaluation can be bench marked. Apart from the spraying conditions, the selection of barrel length was very important in this study. Barrel length was selected on the basis of well-documented previous investigations which have indicated that 8-inch barrel results in relatively higher particle velocity and temperature in comparison to shorter 4-inch barrels [6]. Hence coating quality can improve by selecting longer 8-inch barrel, though longer barrel tends to bring about spitting. It was for this reason that the 8-inch barrel was selected for this investigation.

Table 2: HVOF spray conditions.

Spray Gun	JP-5000 (Praxair/TAFA)
Oxygen Flow Rate	870 l/min at 1.45 MPa
Fuel (Kerosene) Flow Rate	0.38 l/min at 1.17 MPa
Spray Distance	355 mm
Barrel Length	203 mm (8 inches)

<u>Measurement of Particle Strength</u>

Figure 2 shows the schematic of the methodology used to measure the strength of individual powder particles. This equipment is commercially available and generally used for quality control purposes at Fujimi Incorporated. In this method, a powder particle is fixed between a lower platen and a 50 µm flat face indenter. After the particle size in diameter is measured, load is applied at constant rate and the amount of particle deformation is automatically measured with the resolution of 0.01 µm, for a measurement range of 100 µm. Figure 3 shows a schematic of typical measurement result.

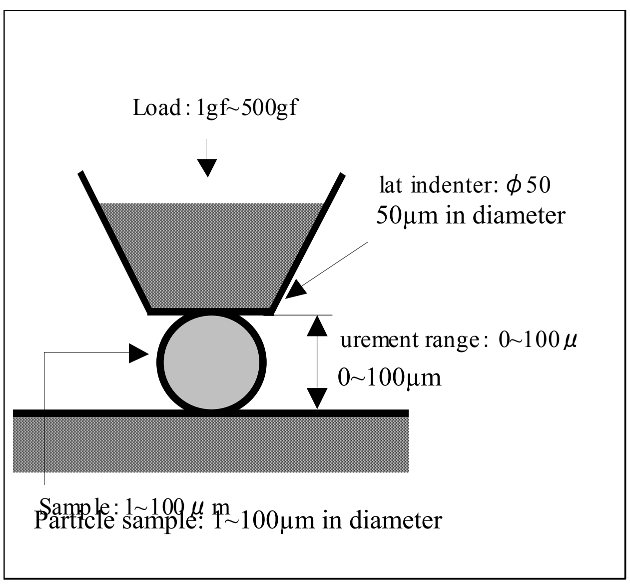

Figure 2: Schematic of particle strength measurement methodology.

The load (P, measured in N) indicating the onset of particle squeezing is automatically measured, which can then be used to evaluate particle strength (S_t) in the units of MPa using the relation [7]:

$$S_t = 2.8\ P/\pi\ d^2$$

where "d" is the particle size in mm. Twenty particles were measured for each spray powder. It is also worth noting that although the selection of these particles was random, there is generally not much variation among the strengths of individual particles in a given batch. This is mainly due to the fact that the particle strength generally depends upon the sintering conditions and not very dependent upon the particle size.

<u>Measurement of Particle Size</u>

Typical size distribution for spray powders was measured using the laser diffraction method. This method utilizes laser diffraction to measure the volume fraction of various sized particles. Results are referred to as $D_{x\%}$, e.g. $D_{50\%}$ represents the average size of particles, and $D_{3\%}$ represents the typical size of the smallest 3% of particles by volume. The distribution of particles resulting from such analysis can generally be assumed Gaussian.

<u>Measurement of Deposit Efficiency</u>

Deposit efficiency was evaluated by measuring the change in weight of powder feeder in real time using a precision balance and then comparing it with the change in weight of the substrate.

<u>Checking the Onset of Spitting</u>

For each powder, the onset of spitting was checked after

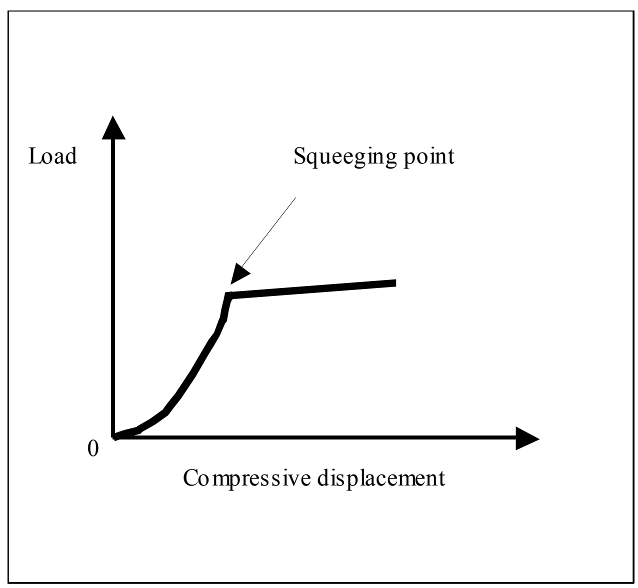

Figure 3: Typical load displacement curve during particle strength measurement.

Table 3: Change of particle size by volume through the powder feeder.

Particle Strength (MPa)		Particle size distribution		
	Feeding	***D***$_{3\%}$ ***(μm)***	***D***$_{50\%}$ ***(μm)***	***D***$_{97\%}$ ***(μm)***
98	*Before*	18.0	35.4	75.5
	After	16.8	32.2	66.7
304	*Before*	18.0	34.6	70.0
	After	18.1	34.7	68.6
725	*Before*	19.5	35.9	73.3
	After	19.4	35.8	72.8

spraying using a robot for ten minutes. This was done by checking the inner diameter of the HVOF gun barrel using 11 mm diameter drill. If the drill was free to enter the barrel before and after spraying, "no-spitting" conditions were assumed. If however spitting occurred during the spraying process, the barrel was clogged, and the drill could not enter the barrel without cleaning the barrel. Such situation meant that spitting has initiated during the ten minutes of spraying. It is worth appreciating that in job shop practice, the spraying continues for hours until such time that barrel becomes so clogged due to spitting, that further spraying could not continue. However the emphasis in the current investigation was the onset of spitting, instead of attaining the conditions of crucial barrel clogging due to spitting i.e., if spraying was to continue beyond ten minutes of spraying adapted in this investigation same level of barrel clogging will eventually result as experienced in job shop practice.

Experimental Results

Particle Size Changes in Powder Feeder

Sometimes poor strength particles can break in the powder feeding mechanism even before they are heated and propelled onto the substrate. This breakage of poor strength powder can alter the typical size distribution to a lower $D_{3\%}$ value, and hence accelerate the onset of spitting. To investigate this behavior, a constant capacity type powder feeder (PL-25NSW) was used to evaluate the damage due to the breaking of poor strength particles in the powder feeder and/or during feeding from the powder feeder. For this purpose, the combustion in the HVOF spray gun was turned off, and powders of various strengths were passed through the powder feeder using nitrogen gas. Each powder was collected back from the brink of the gun, and further analysis on typical particle volume fraction was conducted using the laser diffraction method. Table 3 shows a typical comparison of $D_{3\%}$, $D_{50\%}$ and $D_{97\%}$ values for the low, medium and high strength powders. Figure 4 shows the same distribution for the entire range for the low strength (98 MPa) powder.

Deposit Efficiency vs. Proportion of Fine Particles

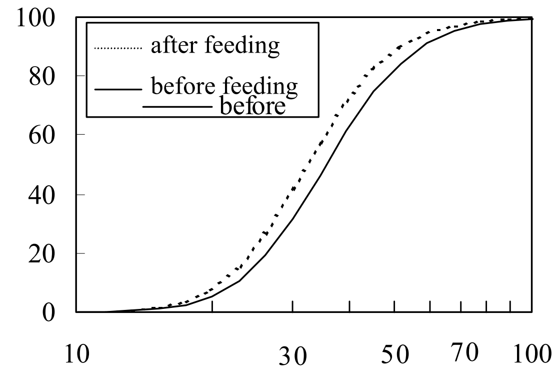

Figure 4: Particle size volume fraction analysis of low strength (98 MPa) powder through the powder feeder.

Figure 5 shows the results of deposit efficiency and $D_{3\%}$ volume fraction readings for three different particle strengths of 98, 304 and 725 MPa. These three powders were selected for this investigation because they represented the behavior of low, medium and high strength powders, respectively. Thus these strengths provided a broad range of particle strengths suitable for this study. Figure 5 also shows the onset of spitting for various strengths and powder particle sizes, and shows that increase in deposit efficiency of poor strength particles was coupled with a pronounced effect on the onset of spitting. Also it can be appreciated from Figure 5, that the volume fraction of fine particle content has a significant influence on the onset of spitting.

Mapping the Onset of Spitting

Having investigated the influence of low, medium and high strength powders, and also the volume fraction of fine particles on the deposit efficiency (Figure 5), a much thorough investigation was made to map the onset of spitting for a variety of particle strengths and fine particle volume fractions. Results of this mapping are shown in Figure 6, in which deposit efficiencies are classified in three main bands. The boundary marking the onset of spitting region is also indicated on this map. It can be appreciated from this map that regardless of the changes in fine particle content, there exists a threshold of minimum powder strength below which the onset of spitting cannot be avoided. Similarly, in terms of particle strength, there exists a threshold of fine particle content below which the onset of spitting cannot be avoided.

Discussion

Figure 5 shows the influence of sintering conditions and thus the particle strength on the deposit efficiency. It can be appreciated from Figure 5 that spitting can be avoided by using medium to high strength (304~725 MPa) particles for a broad range of $D_{3\%}$ volume fraction sizes. Typical range suitable for these powders approximates from just above 15 μm. Below this range of $D_{3\%}$ volume fraction size, the onset of

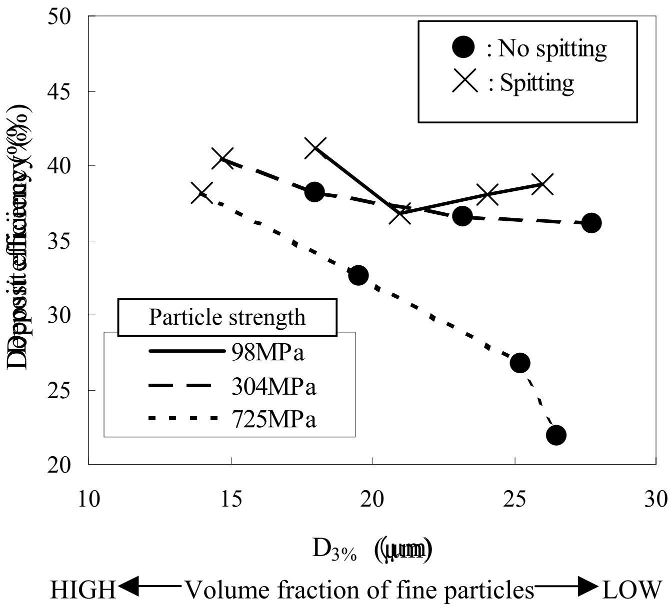

Figure 5: Influence of particle strength and volume fraction of fine particle content on deposit efficiency.

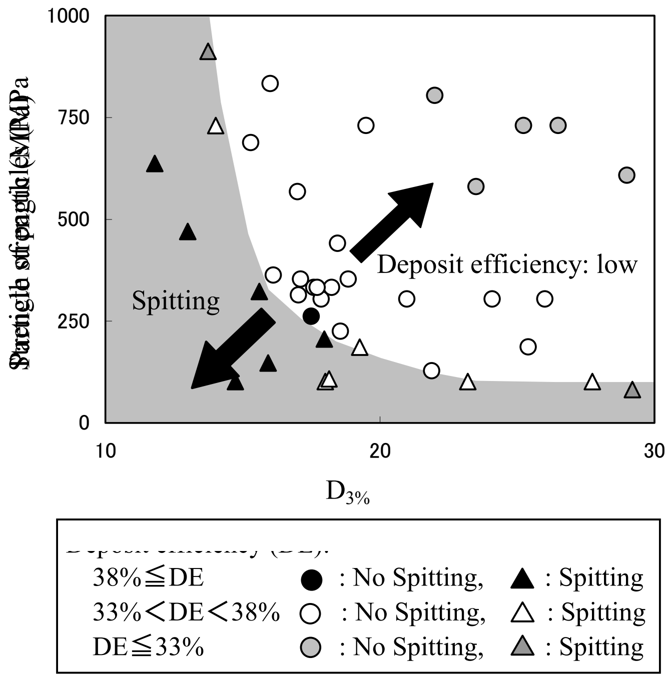

Figure 6: Spitting map of Cr_3C_2-25%NiCr powder using JP-5000 spraying.

spitting could not be avoided over the entire range of low to high strength particles considered in this study. Hence it can be concluded that one important factor leading to spitting, regardless of the changes in powder strength, is the fine particle content within the given nominal size distribution. The deposit efficiency obtained for the no-spitting conditions using medium to high strength particles (304~725 MPa) is however much lower than that of the low strength particles over the entire $D_{3\%}$ volume fraction size considered in this investigation. This can be explained on the basis of the differences in the sintering conditions of low and high strength particles. Generally, deposit efficiency is proportional to the temperature of impacting lamella. During HVOF spraying of poor strength particles, not only the spray particles burst in the flame, but also the surface of spray particles acquires a much higher temperature than its core (center). Hence non-uniform heating of particles occurs during HVOF spraying of poor strength (low sintering temperature) particles. This is due to the fact that lower sintering temperature does not aid the process of grain growth and necking during the sintering process. Hence poor interface between the grains hinders heat conduction and a non-uniform heating of particles occurs during HVOF spraying. The exterior of particles therefore overheats whereas the core remains at much lower temperature. This overheating of particles improves the deposit efficiency, as it prohibits the bouncing of particles upon impact on substrate. However, it also initiates spitting.

Contrary to above, high sintering temperature resulting in higher strength particles aids the mechanisms of grain growth and necking within the powder particles. Hence heat conduction during HVOF spraying is much more uniform and instead of attaining cold core and overheated exterior, high strength particles acquire a more uniform temperature, which is lower than that at the exterior of poor strength (lower sintering temperature) particles. It is due to this lower average temperature of high strength particles which results in its bouncing upon impact on the substrate and therefore relatively lower deposit efficiency.

Investigations relating to the powder particle size changes in the powder feeder (Table 3 and Figure 4) also indicate an important factor which leads to spitting of poor strength particles. This investigation showed that when particle strength is poor i.e. approximately 98 MPa in the current investigation, the breaking of larger particles into smaller ones starts even before these particles subjected to the flame with high velocity and temperature in gun barrel. Figure 5 shows that in such cases the content of small particles increases, which also promotes the onset of spitting during HVOF spraying.

Figure 6 shows the spitting map which summarizes the conditions related to the onset of spitting. This figure shows the boundary of spitting region on the basis of powder particle strength and the amount of fine particle proportion. The most important conclusion from this map is the indication of conditions under which a critical balance among the deposit efficiency, powder particle strength and the amount of fine particle proportion can be achieved. Hence it can be concluded that medium strength powder particles with typical $D_{3\%}$ volume fraction size range of 15 to 20 μm can result in deposit efficiencies in the range of 33 to 38%, without spitting.

Conclusions

Although the specific results in terms of the magnitude of deposit efficiency, particle strength and small particles volume fraction content need to be appreciated in context of the spray conditions and spray material adapted in this investigation, some general conclusions can be drawn to combat the onset of spitting:

1. During HVOF spraying of agglomerated and sintered powders a higher proportion of fine particles within the nominal particle size promotes the onset of spitting.

2. There is a higher tendency to spitting when using low strength powders (even with small proportion of fine particle content) due to powder crushing through the powder feeder.

3. Deposit efficiency falls with the increase in powder particle strength and also with the decrease in fine particle content.

4. It is possible to optimize the deposit efficiency and avoid the onset of spitting by appropriate mapping of particle strength and fine particle content (Figure 6).

References

1. D. Foley, “Spray nozzle inspection, maintenance, and replacement recommendations”, Precision Cleaning, 3 (1995) 43-47.

2. S. Osawa, T. Watanabe and T. Itsukaichi, “HVOF spraying with fine cermet powders”, Proceedings of annual meeting, Japan Thermal Spray Society, 74 (2001) 11-12.

3. S. Osawa, N. Kato, T. Watanabe and T Itsukaichi, “Study of compatibility between preventing spitting and improving deposit efficiency on the HVOF process”, Proceedings of annual meeting, Japan Thermal Spray Society, 73 (2001) 43-44.

4. I. Aoki, T. Watanabe, S. Osawa and T. Itsukaichi, “Characteristics of electroless plating cermet powders and their coatings produced by HVOF”, Proceedings of annual meeting, Japan Thermal Spray Society, 75 (2002) 3-4.

5. N. Kato, K. Ito, S. Osawa and T. Itsukaichi, “Characteristics of HVOF coatings of blended powders of Cr_3C_2+25mass%NiCr”, Proceedings of annual meeting, Japan Thermal Spray Society, 76 (2002) 19-20.

6. J. G. Legoux, B. Arsenault, C. Moreau, V. Bouyer and L. Leblanc, “Evaluation of four high velocity thermal spray guns using WC-10Co-4Cr cermets”, Surface Engineering via Applied Research, Editor C. C. Berndt, ASM International, ISBN 0871706806, (2000) 479-486.

7. Y. Hiramatsu, Y. OKa and H. Kiyama, ”Rapid determination of the tensile strength of rocks with irregular test pieces”, Journal of mining and metallurgical institute of Japan, 81 (1965) 1024-1030.