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Selection Criteria for Wear Resistant Powder Coatings Under Extreme Erosive Wear Conditions

P. Kulu and T. Pihl

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Wear-resistant thermal spray coatings for sliding wear are hard but brittle (such as carbide and oxide based coatings), which makes them useless under impact loading conditions and sensitive to fatigue. Under extreme conditions of erosive wear (impact loading, high hardness of abrasives, and high velocity of abradant particles), composite coatings ensure optimal properties of hardness and toughness. The article describes tungsten carbide-cobalt (WC-Co) systems and self-fluxing alloys, containing tungsten carbide based hardmetal particles [NiCrSiB-(WC-Co)] deposited by the detonation gun, continuous detonation spraying, and spray fusion processes. Different powder compositions and processes were studied, and the effect of the coating structure and wear parameters on the wear resistance of coatings are evaluated. The dependence of the wear resistance of sprayed and fused coatings on their hardness is discussed, and hardness criteria for coating selection are proposed. The so-called "double cemented" structure of WC-Co based hardmetal or metal matrix composite coatings, as compared with a simple cobalt matrix containing particles of WC, was found optimal. Structural criteria for coating selection are provided. To assist the end user in selecting an optimal deposition method and materials, coating selection diagrams of wear resistance versus hardness are given. This paper also discusses the cost-effectiveness of coatings in the application areas that are more sensitive to cost, and composite coatings based on recycled materials are offered.

Keywords abrasion-erosion, detonation spraying, hardmetals, powder coatings, spray fusion, thermal spray, tungsten carbide, wear

1. Introduction

Different kinds of equipment—for example, milling and mixing devices—are subjected to intensive abrasive-erosive wear at extreme conditions (high hardness and strength of abrasives and materials to be ground, high velocity and pressure, cyclic impact loading, elevated temperatures, etc.). It has been shown that in the conditions of impact loading (milling by collision, wear in the stream of hard particles, etc.), materials are exposed to notable strokes. The values of stresses generated in the particles or in the material are approximately an order higher than their strength. As a result, material fractures occur. Based on the structure and properties of materials, fractures may be caused by different mechanisms. With brittle materials, the direct fracture mechanism is dominant; with ductile materials, the mechanism of microcutting or low-cyclic fatigue prevails.[1]

Under these wear conditions, gas thermal coatings and tungsten carbide-cobalt based systems are highly effective.[2] During the last 15-20 years, in the field of thermal spraying, most attention has been paid to various high velocity spray processes (particle velocity exceeding 300 m/s). The high velocity oxyfuel (HVOF) thermal spray technology has facilitated dramatic improvement in the quality and properties of tungsten carbide-cobalt coatings. This is explained by the compressive residual stresses generated in coatings.[2] On the other hand, detonation spraying is another promising thermal spray technology for depositing such coatings with extremely good wear characteristics.[3,4]

Extensive field use of gas thermal coatings gives evidence of the cost-effectiveness of self-fusing (sometimes known as self-fluxing) alloys containing tungsten carbide (WC), applied by spray and fusion methods (flame, plasma, and laser fusion, etc.). Due to their low porosity and metallurgical bond between the basic material and the coating, the above-mentioned fused composite coatings are resistant to significant impact loads.

The aim of this paper is to summarize our earlier works in the study of erosive wear resistance of different thermal sprayed coatings and to propose the criteria (materials and processes, porosity, structure and hardness of coatings) of wear resistance in the conditions of impact erosion coatings for their creation and selection.

P. Kulu and **T. Pihl,** Tallinn Technical University, Department of Materials Technology, Ehitajate tee 5, Tallinn, Estonia 19086. Contact e-mail: pkulu@edu.ttu.ee.

2. Selection of Materials and Processes

To select coating materials and processes for impact erosive resistance, wear testing was conducted. The goal was to produce powder coatings with minimum porosity and high adhesion strength.

Two thermal-spray processes, high velocity spraying (HVS) and spray fusion (SF), were taken into consideration. For HVS processes, detonation spraying (DS) methods were applied: detonation gun spraying (DGS) and continuous detonation spraying (CDS). For DGS, a Perun-S Detonation Gun Spray

Table 1 Spraying Materials, Deposition Technique, and Properties of Coatings

No.	Coating	Composition of Spraying Powder, wt.%	Deposition Technique	Porosity, %	Hardness, HV0.2
Hardmetals					
1	Amdry 927 (a)	WCCo12	DGS (g)	2.1	680/1155 (k)
2	Tafa 1343V (b)	WCCo17	CDS (h)	2.9	1300
3	Tafa 1350VM	WCCo10Cr4	CDS	0.7	1230
4	Kiev BK9B (c)	WCCo9	DGS	2–3	1310
5	Kiev BK15B	WCCo15	DGS	2.7	945
6	Desirec VK15 (d)	WCCo14Fe8	DGS	4.1	815
Self-fluxing alloys					
7	Tafa 1275H	NiCr16Si4Fe4B3.5	CDS, SF	1.7	805
8	12494 (e)	NiCr11Si2B2	CDS, SF	1–2	430
9	12495	NiCr13Si4B3	CDS, SF	1–2	560
10	12496	NiCr15Si4.5B3.5	CDS, SF	1–2	700
Composite powders					
11	12494+15wt.% WC-Co (f)		FSF (i)	2–3	675/1410
12	+25wt.% WC-Co		FSF, LSF (j)	2–3	685/1445
13	+50wt.% WC-Co		FSF	2–3	735/1465
14	12495+25wt.% WC-Co		FSF	2–3	755/1400
15	12496+25wt.% WC-Co		FSF	2–3	820/1410

(a) Sulzer Metco Inc.
(b) Tafa Inc.
(c) Institute of Welding, Kiev, Ukraine.
(d) Recycled disintegrator milled hardmetal powder (+32–40μm), Tallinn Technical University, Estonia.
(e) Castolin SA, Switzerland.
(f) Desirec VK15 (No. 6) hardmetal powder +60–125μm.
(g) DGS: Detonation Gun Spraying, Perun-S, Institute of Welding, Kiev, Ukraine.
(h) CDS: Continuous Detonation Spraying, HVOF Spraying, Tafa JP5000, Tafa Inc.
(i) FSF: Flame Spray Fusion.
(j) LSF: Laser Spray Fusion.
(k) Hardness of metal matrix/hard phase.

System (Institute of Welding, Kiev, Ukraine) with propane and oxygen was used. For CDS, the HVOF Machine Mounted Model Tafa JP5000 (Tafa Inc., Concord, NH) was used. For the SF processes, the flame spray fusion (FSF) method and the corresponding flame spraying equipment (Castolin SA, Lausanne, Switzerland) and laser spray fusion (LSF) equipment were used.

The coating materials that were used can be roughly divided into three groups: tungsten carbide-cobalt (WC-Co) based hardmetal powders, nickel based self-fluxing alloy (NiCrSiB) powders, and composite powders on the basis of NiCrSiB alloy powders and hardmetal powders (Table 1). Hardmetal powder produced by disintegrator milling technology from used (recycled) hardmetal parts and cutting plates was used.[5,6]

Characterization of impact erosion (study of wear rate and wear mechanism) was performed in an impact erosion wear tester to test materials in an abradant particle jet (Fig. 1).[7] Our testing method involved abrading the specimen with a stream of abradant—quartz sand with particle size of abrasive 0.1-0.3 mm and abrasive hardness 1100-1200 HV. The velocity of abrasive particles was 80 m/s. To determine the influence of abrasive hardness on the wear rate, the abrasives of different hardness (from 120-2000 HV)—limestone, glass, iron oxide, quartz, and corundum—were also studied. The measurements of weight loss permitted calculations for weight and volume losses as a measure for wear rate; that is, the loss of mass or volume per one kilo of abrading material in mg/kg and mm^3/kg, respectively. The relative wear resistance, E_v, was calculated as the ratio of the volume wear rates of the studied and the reference material. A reference material, normalized steel of 0.45% C of hardness 200 HV, was used.

For wear testing at elevated temperatures, a special specimen heating system was built; stainless steel type 18/10 was used as a reference material.

3. Criteria for Coating Selection

3.1 Porosity and Structure of Coatings

Based on the impact erosion study of thermally sprayed coatings deposited by different methods (flame and plasma spraying, DGS, SF), it was shown in our previous studies[1,8-10] that only coatings with low porosity (porosity less than 5%) worked under the conditions of impact erosive wear.[1]. The medium and high porosity coatings (porosity more than 5%) of the same hardness laid by different methods (flame, plasma, and detonation spraying) may differ by one order of magnitude in their wear resistance under analogous wear conditions. The relative impact erosive wear resistance of high porosity coatings was low (less than one).[10] This means that high velocity spraying only or flame spray and fusion guarantee low porosity (in the range of 1-3%) and high wear resistance in the conditions of impact erosion. The porosities of hard coatings selected in this paper (Table 1) were in the range of 0.7-4.1%.

Based on the different fracture mechanisms of wear by impact erosion under different wear conditions, it was shown by the present authors that only coatings with optimal structure guarantee high wear resistance in the conditions of impact erosive wear. [9,10] In the case of oblique impact erosion (at small and medium impact angles), where the wear rate decreases with an increase in the hardness, and the mechanism of microcutting

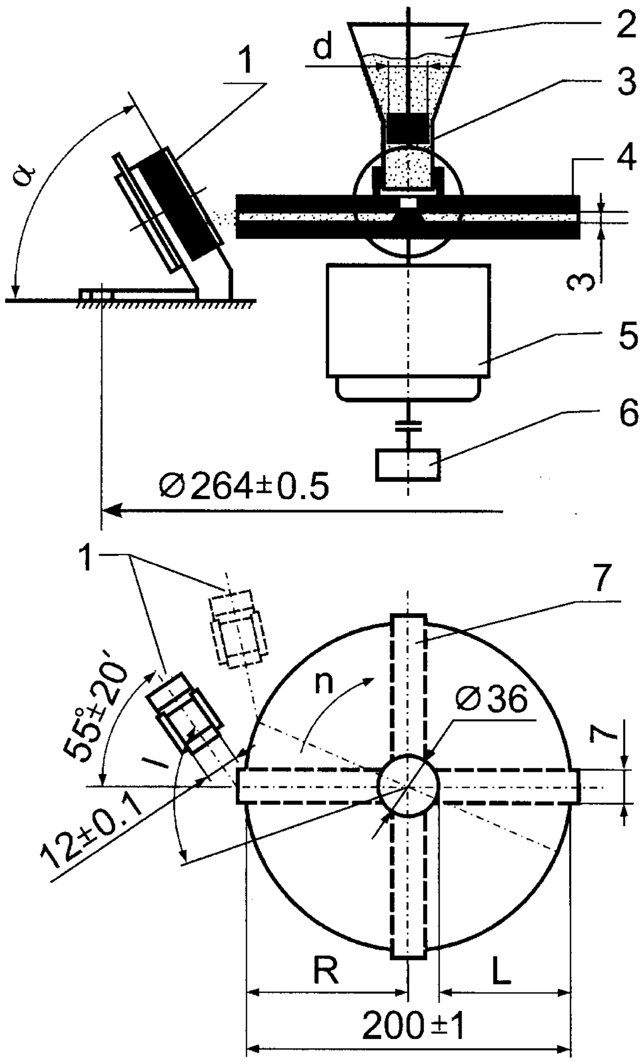

Fig. 1 Impact erosive wear tester for testing materials in abradant particles jet: (1) specimens, (2) abradant, (3) shield, (4) rotor, (5) drive motor, (6) rotation frequency gauge, and (7) radial channels

is dominating, the framed structure is preferred (Fig. 2a). The hard phase content must exceed 50%. In the case of normal impact, the matrix structure with hard phase content of less than 50% is preferred (Fig. 2b).[8,9] In the conditions of mixed impact erosion, such as in different mixing and grinding equipment, the optimal structure of WC-Co and other carbide-metal based hardmetal coatings, instead of a simple cobalt matrix containing particles of WC or other carbides, is a Co (Ni) matrix based structure containing particles of WC-Co (or other hardmetals) agglomerated granules or particles of WC-Co (or other carbides) based hardmetal.[10] This is the so-called "double cemented" matrix structure (Fig. 3a). A similar structure is obtainable with the help of hardmetal powders coated with metal (Co or Ni) and by the HVS method. Another way to manufacture such complicated cemented structures is spray and fusion of composite powders based on WC-Co or other carbide based hardmetal powder and, for example, NiCrSiB self-fluxing alloy powder. The resulting structure consists of WC-Co hardmetal particles in the

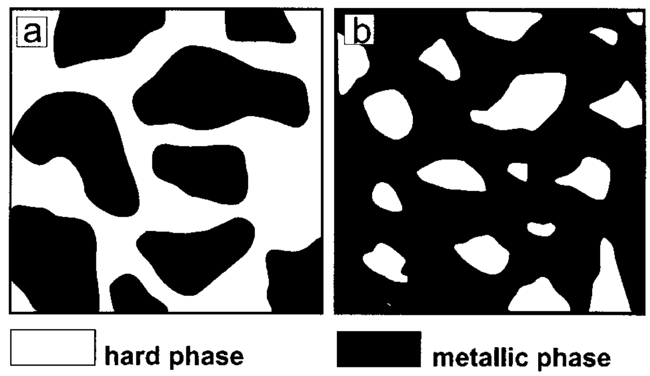

Fig. 2 Recommended structures for **(a)** oblique impact and **(b)** normal impact

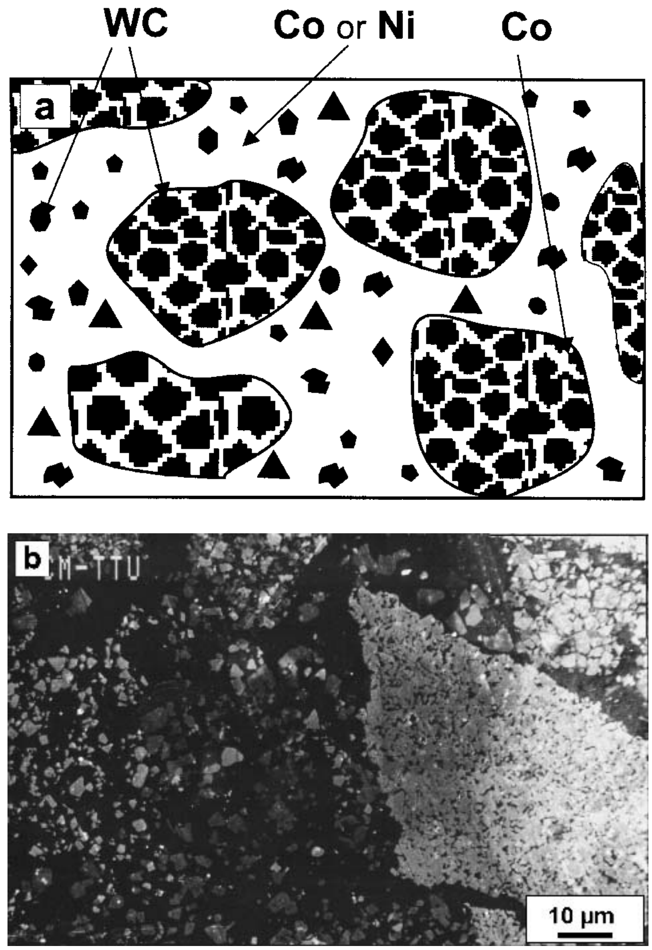

Fig. 3 Optimal cermet structure of coating in the conditions of impact erosion: **(a)** recommended double cemented, **(b)** produced by spray and fusion [NiCrSiB+25 wt.% (WC-Co)]

Ni-alloy based matrix with small dissolved tungsten carbide particles (Fig. 3b).[3,4,8]

In the conditions of normal impact erosion, where a direct fracture or low-cyclic fatigue fracture mechanism dominates, out of the residual stresses in coatings, compressive stresses are

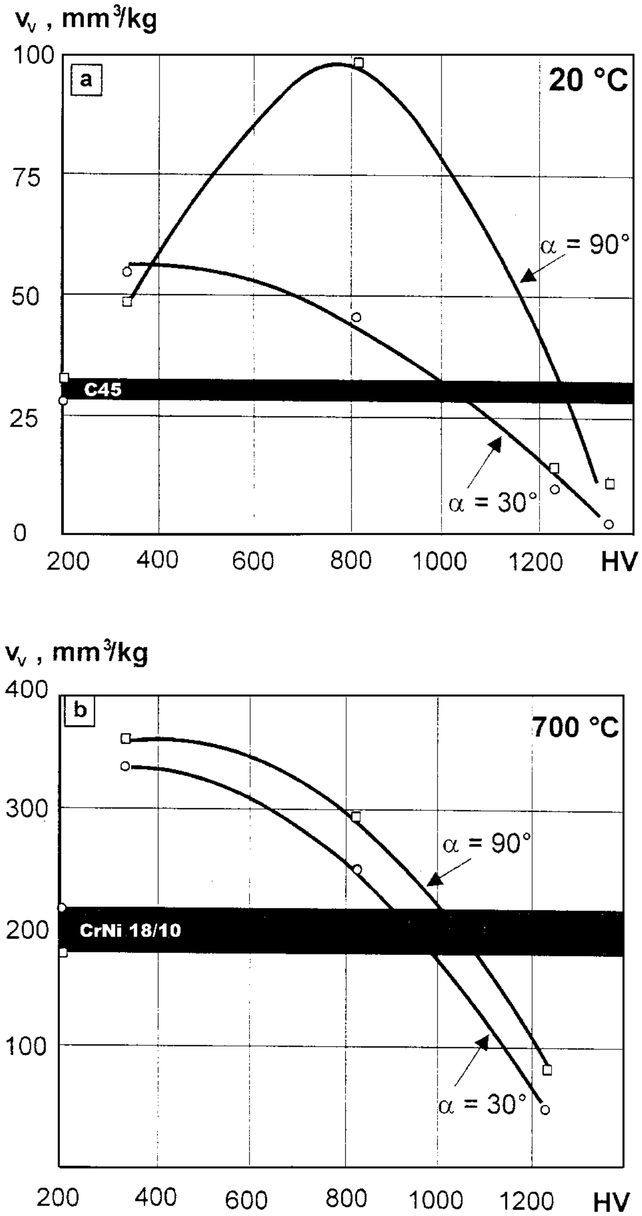

Fig. 4 Dependence of wear rate from impact erosion at impact angles 30° and 90° on the hardness of CDS coatings: **(a)** at room temperature, **(b)** at elevated temperature (700 °C) (shaded areas—wear rates of reference materials—steel 0.45%C and stainless steel 18/10)

favorable. Such compressive stress in coatings is obtained by HVOF-spraying or by thick composite coatings manufactured by spray and fusion,[2] which guarantees high erosive wear resistance of coatings.

3.2 Hardness of Coatings

At room temperature, for HVS coatings with impact erosion at small impact angles (Fig. 4a, α = 30°), wear decreases with an increase in coating hardness due to dominating microcutting wear mechanisms.[2,10] When great impact angles are applied, an increase in coating hardness up to 700-800 HV causes an increase in the wear rate (Fig. 4a, α = 90°); with coatings at higher hardness (HVOF-sprayed WC-Co hardmetal coating), an increase in coating hardness causes a decrease of the wear rate due to the dominating direct fracture or low-cyclic fatigue fracture wear mechanism.[2,10] It is similar to the wear mechanism of hardmetals at abrasive-erosive wear[11] but differs from the mechanisms observed under other abrasive wear conditions.[12,13]

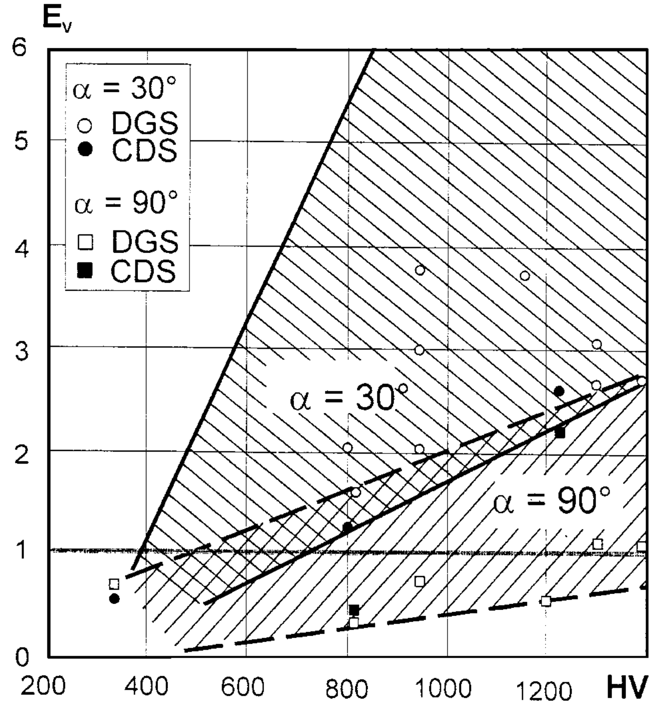

Fig. 5 Relative impact erosive wear resistance vs sprayed coating hardness at impact angles 30° and 90° for DGS and CDS coatings

At elevated temperatures (600-800 °C), the mechanism of impact wear resembles that at oblique impact (α = 30°) and normal impact (α = 90°) (Fig. 4b). In both conditions of wear, plowing of the abraded surface takes place, and as a result, abraded material is removed.[10,14]

The dependence of relative wear resistance on sprayed coating hardness is illustrated in Fig. 5. As is shown, the main tendency of sprayed coatings is as follows: both at small and great impact angles, an increase in the hardness of HVS coatings leads to an increase in their impact erosive wear resistance. At an oblique impact angle (30°), the wear resistance of the best sprayed WC-Co coatings is about 10-12 times higher than that of the reference material, uncoated steel (points are outside of Fig. 5). At normal impact erosion, the wear resistance of the best sprayed coating exhibited wear resistance 2-2.5 times higher than that of uncoated steel. The effect of spray and fusion composite coating hardness on the relative wear resistance varies. At small impact angles, the wear resistance of fused coatings increases with an increase in coating hardness ($E_v > 1$) (Fig. 6.). At great impact angles, an increase in coating hardness causes a decrease in their wear resistance ($E_v < 1$). The effect of the coating hard phase content (composites No. 11-13, Table 1) on the wear resistance in the hard phase range (from 15-50 wt.%), as

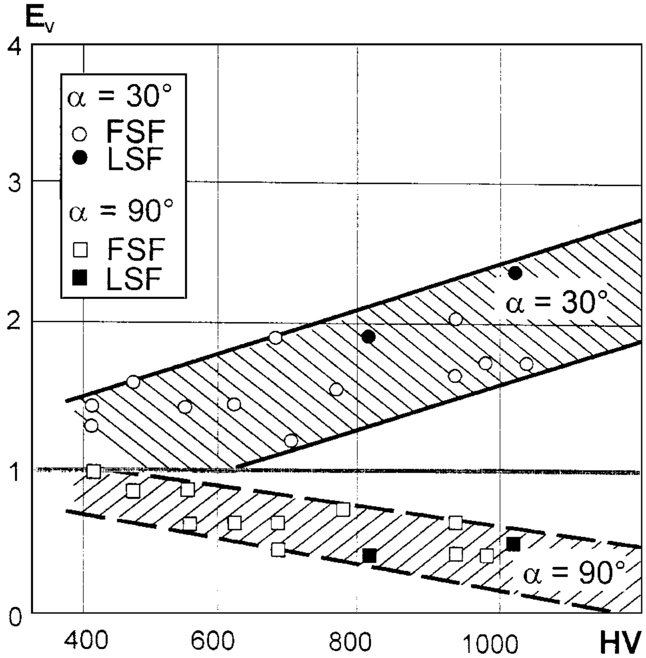

Fig. 6 Relative impact erosive wear resistance vs spray and fused coatings hardness at impact angles 30° and 90°

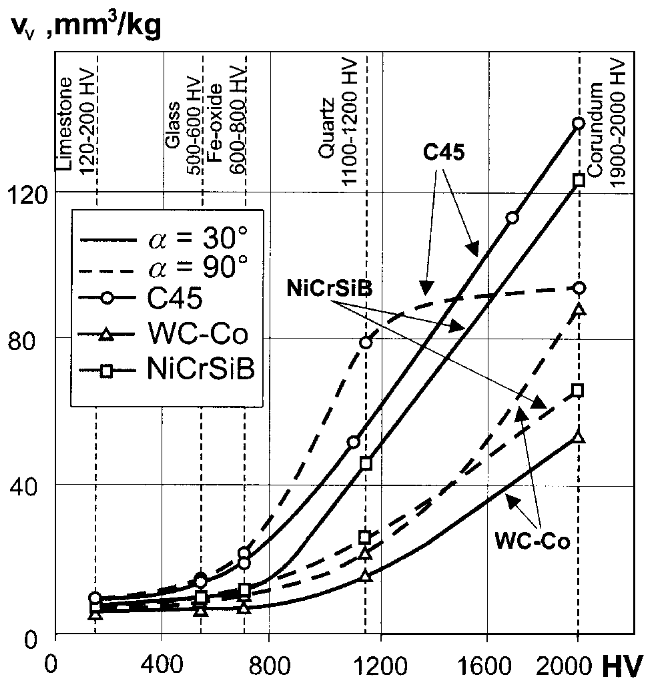

Fig. 7 Dependence of impact erosive wear rate on the hardness of abrading material: HVS WC-9Co (No. 4), NiCrSiB coating (No. 10), and the reference material of steel 0.45%C at impact angles 30° and 90°

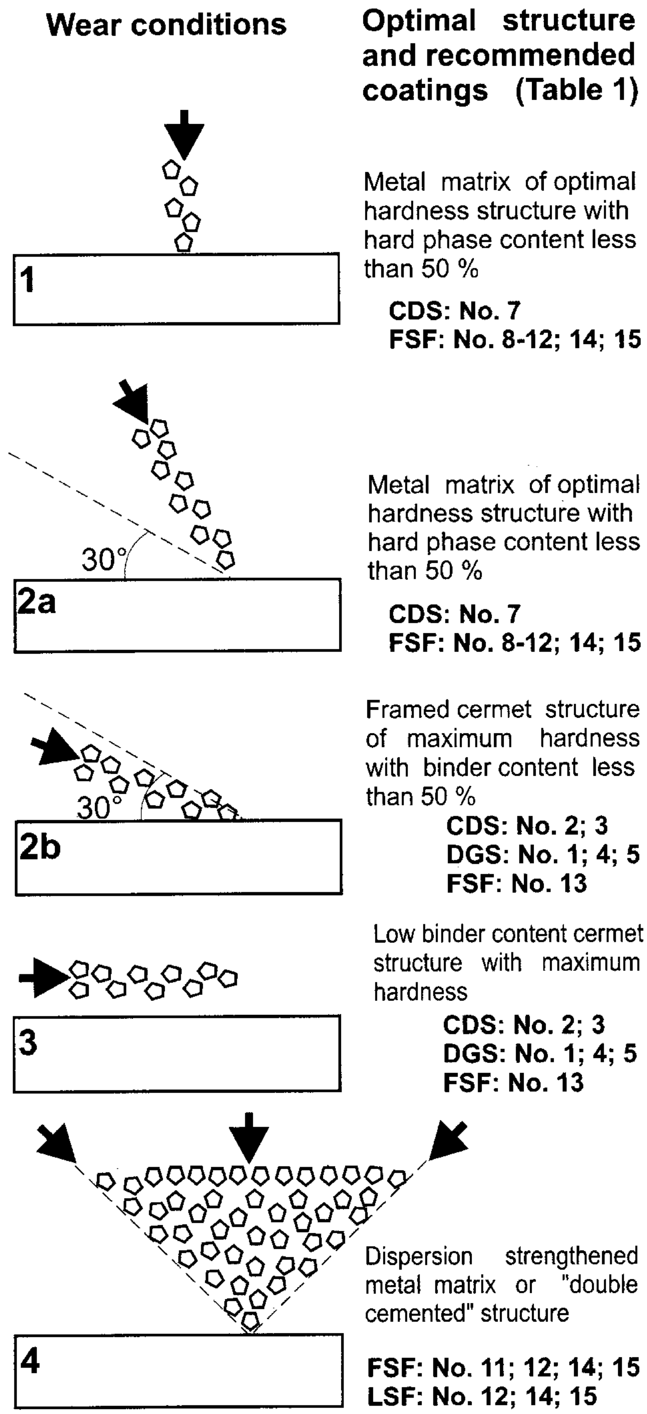

Fig. 8 Optimal structures of wear resistant coatings and recommended coatings for different impact erosion wear conditions: (1) at normal impact erosion (α = 90°), (2a,b) at oblique impact erosion (0 < α < 90°), (3) at tangent erosion, (4) at mixed impact erosion

shown in our studies, was significant.[3,4] An increase in the amount of hard phase particles of composite coatings up to 20-30% led to an increase in the wear resistance under the wear condition similar to normal and at oblique impact (α < 30°).[3] The influence of a further increase in hard phase particle content on the relative wear resistance varies. At small impact angles, wear resistance is almost unchanged; at normal impact, a further increase in the hard phase content causes a monotonic decrease in the relative wear resistance.[3]

Test results showed that the composite coatings based on self-fluxing alloy and hardmetal powder applied by FSF had relative wear resistance exceeding 1.3-2.1 times that of pure NiCrSiB coatings.[8] These composite coatings are useful in providing new high-wear resistance solutions, combining toughness of self-fluxing alloys with hardness of tungsten carbide.

3.3 Hardness of Abrading Materials

Experimental studies of impact erosion with an abradant of different hardness (from 120-200 HV up to 1900-2000 HV)[1] have given evidence of the great influence of abradant hardness on the wear rate of coatings. The dependence of the wear rate from impact erosion on the hardness of the abrading material is shown in Fig. 7. The so-called S-curves of two different coatings (hardmetal and self-fluxed Ni-alloy based) are given as examples. To guarantee high wear resistance of coatings at oblique impact, their hardness must exceed the hardness of the abrasive or the material to be treated. At normal impact by the prevailing fatigue fracture mechanism, the influence of abradant hardness on the wear rate is insignificant.[1]

The results of laboratory tests with abrasives of different hardness and particle shape[1] confirm that a direct correlation exists between the abrasive particle shape and the wear rate; increases in particle angularity result in a significant increase in the abrasive erosive wear.

4. Rules for Selection

To select powder coatings for abrasion-erosion conditions, the peculiarities of powder coatings (porosity, hardness) and the conditions of wear (hardness of abrasive, velocity of particles) must be taken into consideration.

High impact erosive wear resistance of powder coatings is based on the following (see Fig. 8).

- Minimum porosity: A high velocity thermal spray process guarantees the high density of coatings (porosity less than 3%) and high wear resistance at extreme conditions of wear (abrasive-erosive wear resistance exhibited 10-12 times higher wear resistance than the reference material, uncoated steel).
- Optimal hardness of coatings: Hardness depends on the erosion conditions. To guarantee high abrasive-erosive wear resistance at small impact angles, the hardness of coatings must be at a maximum and higher than that of the abrasive. At great impact angles, the optimal level of hardness is recommended.
- Optimal structure: Framed structure is ideal for oblique impact, and matrix structure for normal impact. For mixed conditions, the "double cemented" matrix structure is ideal (metal matrix structure containing particles of WC-Co granules or WC-Co particles).
- Hardness of abradant: To guarantee high impact erosive wear resistance, hardness of coatings must exceed that of the abrasive or the material to be treated.

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