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Improved Hardfacing for Drill Bits and Drilling Tools

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New flame spray hardfacing, DSH (DuraShell® Steel Hardfacing, US patent pending), was developed to improve thermal conductivity, abrasion wear, and erosion resistance for subterranean drilling application. The materials consisted of spherical cast WC/W_2C and Ni-Si-B alloy powders. The hardfacing compositions were tailored for various processes such as flame spray and laser cladding. Typically, the hardfacing comprised hard tungsten carbide particles being uniformly distributed in a tough Ni-alloy matrix. The hardness of WC/W_2C exceeded 2300 $Hv_{.3}$ and that of Ni-alloy matrix varied from about 400 to 700 $Hv_{.3.}$ High- and low-stress abrasion resistances of these hardfacing materials were characterized and compared to the conventional hard coatings of cast WC/W_2C and Ni-Cr-Si-B-Fe. The increase in thermal, wear, and erosion resistances of the hardfacing improved the durability of PDC (polycrystalline diamond compact) steel body bit and drilling tools and their cost-effective performance. Several case studies of DSH hardfacings on drill bits were described.

Keywords flame spray, fluidity, laser cladding, PDC steel bit, WC/W_2C

1. Introduction

PDC (polycrystalline diamond compact) bits have dominated petroleum and gas drilling in recent years. The body of PDC bits can be manufactured from two different materials, steel and tungsten carbide matrix. The matrix body bit is manufactured by infiltrating tungsten carbide particles, macrocrystalline WC or chill-cast and crushed WC/W_2C, or mixture of them, with a Cu-Ni-Zn-Mn alloy; the steel body bit, machined and manufactured from steel stock, is better able to withstand impact load than matrix body bit. The main disadvantage of steel is that it is less erosion resistant than tungsten carbide matrix and, consequently, more susceptible to wear and erosion by abrasives in the drilling fluids and contacting the rock formation. To protect the steel bit body from erosion damage in service, a more wear- and erosion-resistant coating is generally sprayed on the surface. The challenge to manufacture a durable PDC steel body bit lies in the formulation of hardfacing material which has s wear and erosion resistances equivalent to or better than that of the matrix body, macrocrystalline tungsten carbide infiltrated with Cu-Ni-Zn-Mn alloy (HDK).

Flame spray Commercial A and oxyacetylene torch-deposited Commercial B hardfacings have been used for surface enhancement on PDC steel bit and bi-center steel bit, respectively, to mitigate wear of the steel body for more than 10 years. The former uses 10-160 μm angular cast-and-crushed WC/W_2C and the latter relatively large spherical cast WC/W_2C, 750-1200 μm. Both use a Ni-Cr-Si-B-Fe alloy as a binder. As drilling conditions have become more aggressive and harsher in recent years, Commercial A and Commercial B hardfacings provide marginal protection for steel body in most drilling applications, especially for North America where the business model demanding multiple uses of the bit body for cost-effective drilling. To have a ''Matrix-type Armor'' for steel body bit, wear- and erosion-resistant hardfacings via flame spray and laser cladding techniques were then formulated with spherical cast WC/W_2C and a Ni-Si-B alloy powders—henceforth referred to as DSH (Durashell Steel Hardfacing) for flame spray and LDSH for laser cladding.

Table 1 lists the powder composition of DSH, LDSH, and Commercial A, B, and C hardfacings. Commercial C was produced by laser cladding. Nonmetallic elements B and Si are commonly used in the hardfacing binder alloy to provide fluxing during deposition. The higher the Si + B content in the hardfacing powder the more effective the fluxing. DSH hardfacing generally had significant higher fluxing agent, Si + B, compared with current commercial hardfacings. Various compositions of DSH hardfacings were developed for large area applications such as blade faces and gauges of PDC bit with the above mentioned techniques. Spherical WC/W_2C content and Ni-Si-B alloy

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Table 1 Composition of hardfacings

	Composition, wt.%	
Hardfacing	**WC/W_2C**	**Binder phase**
Commercial A	55	45 (Ni-7.5Cr-3Fe-3.5Si-1.5B-0.3C)
Commercial B	68	32 (Ni-9.5Cr-3Fe-3Si-1.6B-0.6C)
Commercial C	60	40 (Ni-9.5Cr-3Fe-3Si-1.6B-0.6C)
DSH (flame spray)/ LDSH (laser cladding)	40-90	60-10 (Ni-xSi-yB); $X, y > 1$

in the DSH hardfacing determined its fluidity during deposition. If angular WC/W_2C was used, because of more surface areas of carbide, then it required more fluxing agents in the blended powders. Typical commercial hardfacing with relatively low Si + B content in the binder (Table 1) had poor deposited hardfacing for drill bit application. Angular WC/W_2C and additions of Cr, Fe, and C in the binder detracted fluxing action and reduced toughness of the hardfacing. Apparently, fluidity was essential for thermal spray techniques. The use of spherical cast WC/W_2C and Ni-Si-B in DSH hardfacing was to maximize fluidity and to optimize WC/W_2C volume content, apart from taking advantage of its high hardness and minimum stress raiser. Naturally, DSH composition was tailored to provide steel body bits and tools with ''Matrix-Type Armor.''

2. Experimental Process

To evaluate hardfacing, 2.5 cm × 7.6 cm × 1.0 cm AISI 1018 coupons were deposited with DSH hardfacings using flame spray and laser cladding processes. The coupons with Commercial A, B, and C hardfacings were also produced for evaluation.

The hardfaced coupons were evaluated metallographically. The hardness of Ni-alloy matrix and tungsten carbide were measured using Vickers' hardness tester. Phases and their compositions in the matrix of the hardfacing, revealed by light surface etch with Marbles reagent, were identified and analyzed semi-quantitatively by SEM-EDX technique. The average volume fraction of WC/W_2C in the hardfacing was determined by Simages Quantitative Images Analysis.

Low- and high-stress wear resistances of the hardfacings were evaluated in accordance with the recommended guidelines of the American Society of Testing Materials, ASTM G65 and ASTM B611, at Kennametal Research Lab, Rogers, Arkansas. The hardfacing surface was ground to the range of 0.5-0.76 μm AA before test. For ASTM B611 test, the hardfacing was loaded with 196 N (44 lbs) against AISI 1020 wheel in the slurry of 30 mesh (590 μm) angular-fused aluminum oxide for 500 revolutions. In ASTM G65 test, semi-rounded Ottawa silica sand of 50/70 mesh (210/300 μm) was introduced between a test hardfacing and a rotating wheel rimmed with a chlorobutyl rubber. The hardfacing was pressed against the rotating wheel at 130 N (30 lbs) for 6000 revolutions. The weight of the hardfacing was measured before and after test, and then its weight loss was calculated and converted to cubic centimeter per 1000 revolutions.

Fluidity of hardfacings were qualitatively evaluated by observing flow of the deposits on 2.5 cm × 7.6 cm × 1.0 cm AISI 4145 coupons during flame spray and on surface textures of as-deposited hardfacings.

3. Results and Discussion

Hardfacing system generally is divided into surfacing alloy and tungsten-based alloy. Surfacing alloys include steel, Mn steel, Cr-Co-W and Co-alloy, Fe-Cr, and Ni-Cr-B alloys, while tungsten-based alloy contains tungsten carbide and a Fe- or Ni-alloy. Most surfacing alloys have wear-resistant particles formed during solidification from deposition (Ref 1-3). Ni-Cr-B-Si alloys with WC/W_2C have also been used in Commercial A, B, and C hardfacings; variants of these hardfacing systems were investigated for abrasive wear resistance enhancement (Ref 4). By contrast, DSH hardfacings were deposited with predetermined content of wear-resistant particle WC/W_2C in a Ni-Si-B matrix in which Ni_3B precipitates was found after solidification.

However, tungsten carbide in the hardfacing melted at much higher temperature than Ni-Cr-Fe-Si-B-C and Ni-Si-B binders; depending on deposition techniques and particles size of tungsten carbide, a small amount of tungsten carbide particle was dissolved during deposition, which was also observed by Badish and Kirchgaßner (Ref 5). Consequently, W and C were incorporated into the binder alloy during solidification. In general, W and C dissolution strengthened the matrix phase and increased its wear resistance (Ref 6), but reduced its overall toughness of hardfacing. Therefore, the chemistry of phases and its size and distribution in the hardfacing matrix had predominant influence on its wear characteristics and impact resistance.

Typical microstructure of DSH and LDSH hardfacings, produced, respectively, by flame spray and laser cladding, showed crack-free and dense structure with a uniform distribution of spherical cast WC/W_2C hard particles throughout the thickness, while Commercial A and B hardfacings exhibited pores or micro-cracks (Fig. 1a-d). The apparent porosity of DSH and LDSH hardfacings ranged from 0.06 to 0.6 vol.%, depending on variability of deposition parameters such as temperature, torch-to-part standoff, binder chemistry, and powder feed rate. Commercial C, a commercial laser cladding applied to drilling tools (Ref 7, 8), had microstructure similar to LDSH. The hardfacings containing cast WC/W_2C with different Ni binder alloys are listed in Table 2. Hardness of WC/W_2C was between 2120 and 2499 $Hv_{.3}$ and matrix hardness varied from 440 to 537 $Hv_{.3}$. DSH and LDSH contained a simple low-melting-temperature binder, Ni-Si-B. In Commercial A, B, and C hardfacings, alloying elements such as Cr, Fe, and C were added to Ni-Si-B to strengthen the matrix, but caused brittleness to hardfacings without any significant hardness improvement in the binder phase

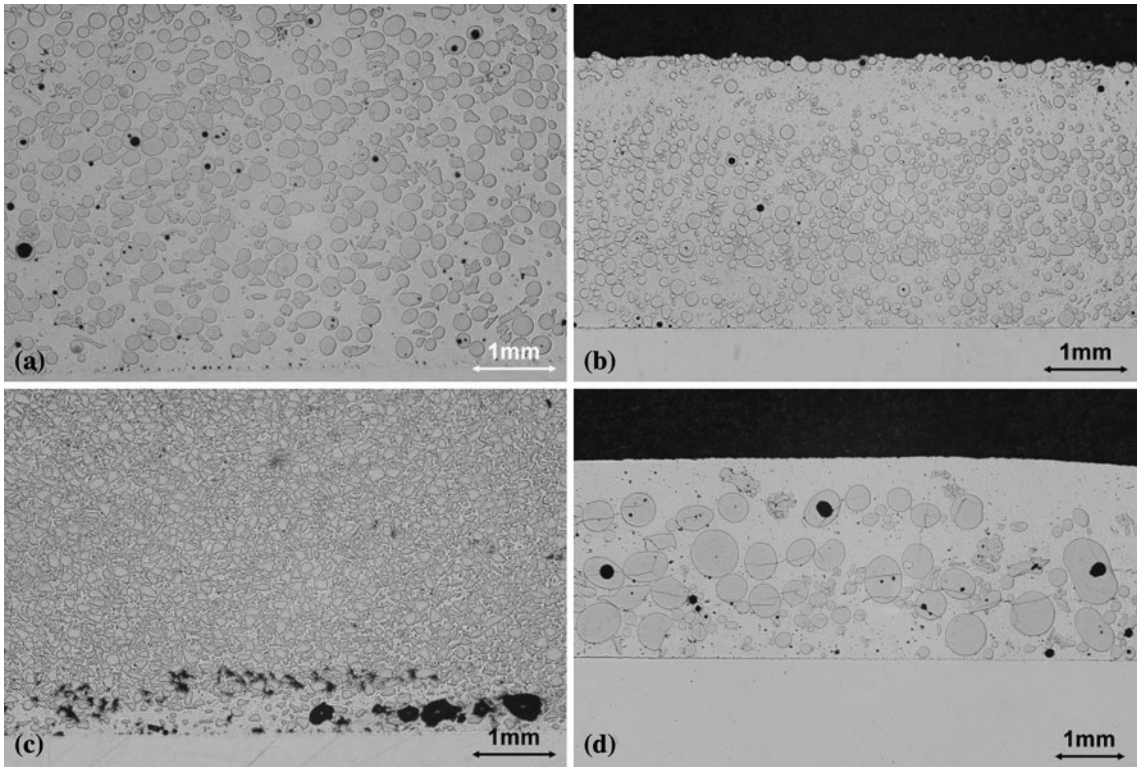

Fig. 1 Typical microstructure of hardfacings (a) DSH, (b) LDSH, (c) Commercial A, and (d) Commercial B

Table 2 Characteristics of various hardfacings

Hardfacing	Carbide size, μm	Carbide shape	Volume fraction of carbide, %	Hardness of carbide, $Hv_{.3}$	Hardness of matrix, $Hv_{.3}$
Commercial A	10-160	Angular	41.4	2499	440
Commercial B	750-1200	Sphere	40.7	2377	524
Commercial C	80-210	Sphere	40.0	2216	581
LDSH	80-210	Sphere	37	2120	450
DSH	160-250	Sphere	57.2	2318	537

(Table 1, 2). High incidences of microcracks were observed in these commercial hardfacings on PDC steel bits and tools after deposition and service loadings.

Matrix phase compositions analyzed by SEM/EDX are summarized in Table 3, and their corresponding microstructures are shown in Fig. 2 and 3. A comparison in matrix microstructure between DSH and Commercial A, resulting from solidification of Ni-4.56Si-3.27B and Ni-7.5Cr-3Fe-3.5Si-1.5B-0.3C from flame spray, is shown in Fig. 2(a) and (b), respectively. DSH comprised spherical WC/W_2C, and Commercial A had angular WC/W_2C. DSH hardfacing matrix was composed of Ni-8.64W-3.53C-3.03Si-3.59B (higher-melting-temperature phase) and Ni-11.0B-0.43Si (lower-melting-temperature phase). Dissolution of fine WC/W_2C particles into the binder phase resulted in the presence of W and C in a higher-melting-temperature phase and submicron (Ni, W) B precipitates (α3) aggregated by WC/W_2C particles. The matrix of Commercial A consisted of a Ni-11.96W-4.66Cr-2.53Fe-2.82B-1.12Si-2.86C (β1) and Ni-3.23Cr-1.66Fe-9.66B-1.89Si (β2) phases with W-13.93Ni-5.62Cr-0.6Fe-8.77B-10.97C (β3), possibly (W, Ni, Cr) (B, C) hard phase dispersed throughout the latter phase, which was the lowest-melting-temperature phase in this matrix system.

The difference in matrix microstructure between LDSH and Commercial B is revealed in Fig. 3(a) and (b). The former was solidified from Ni-3.39Si-1.78B alloy and the latter from Ni-9.5Cr-3Fe-3Si-1.6B-0.6C. Both hardfacings contained the same particle size of spherical cast WC/W_2C, 80-210 μm. Both matrixes showed dendritic microstructure. LDSH comprised Ni-15.59W-2.13B-1.39Si-2.63C dendrite (δ2) in Ni-9.29B-1.11Si (δ1) matrix in which a few WC (δ3) particles dispersed. Commercial C showed Ni-6.21W-5.22Cr-4.29Fe-5.98B-1.35Si-6.7C dendrites (ε1) in Ni-4.04Cr-2.84Fe-18.3B-1.07Si matrix (ε2) in which W-18.35Ni-7.8Cr-0.84Fe-8.86B-11.42C (ε3)

Table 3 Matrix phase composition of DSH, LDSH, and commercial hardfacings

			Chemical composition, wt.%						
	Process	**Phase**	**Ni**	**W**	**Cr**	**Fe**	**B**	**Si**	**C**
DSH	Flame spray	α1	88.58	…	…	…	11.0	0.43	…
		α2	81.16	8.64	…	…	3.59	3.03	3.53
		α3	64.37	17.99	…	…	12.91	3.96	…
Commercial A	Flame spray	β1	74.08	11.96	4.66	2.53	2.82	1.12	2.86
		β2	83.55	…	3.23	1.66	9.66	1.89	…
		β3	13.93	60.11	5.62	0.60	8.77	…	10.97
LDSH	Laser cladding	δ1	85.69	…	…	…	9.29	1.11	…
		δ2	77.91	15.59	…	…	2.13	1.39	2.63
		δ3	…	91.87	…	…	…	…	8.13
Commercial C	Laser cladding	ε1	70.24	6.21	5.22	4.29	5.98	1.35	6.70
		ε2	73.75	…	4.04	2.68	18.3	1.07	…
		ε3	18.35	52.76	7.80	0.84	8.86	…	11.42

Note: Weight percent of Carbon and Boron are overestimated using SEM/EDX Technique with Quantax 200 software

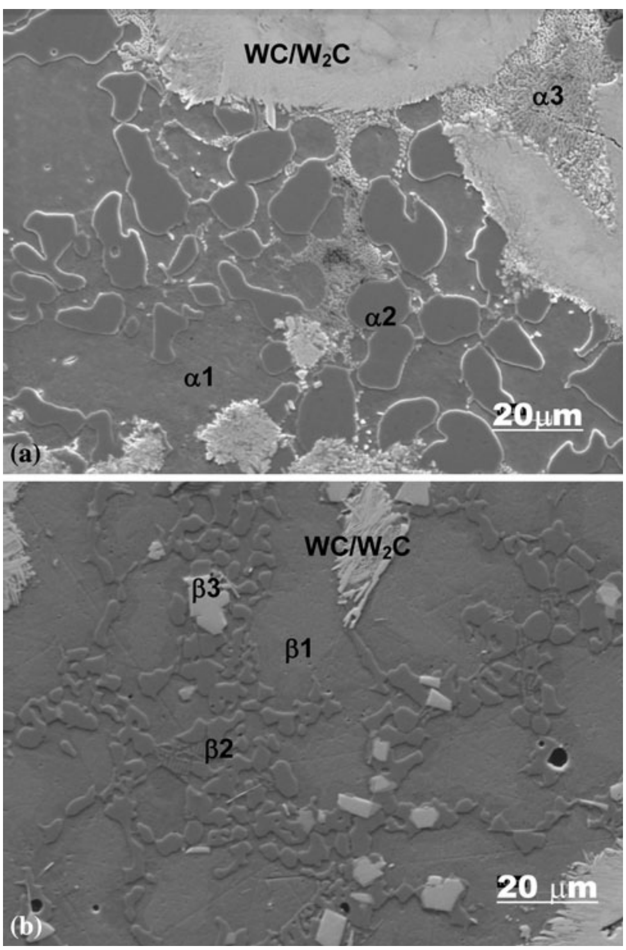

Fig. 2 SEM micrographs of etched surface revealing the typical matrix microstructure of (a) DSH hardfacing and (b) Commercial A hardfacing

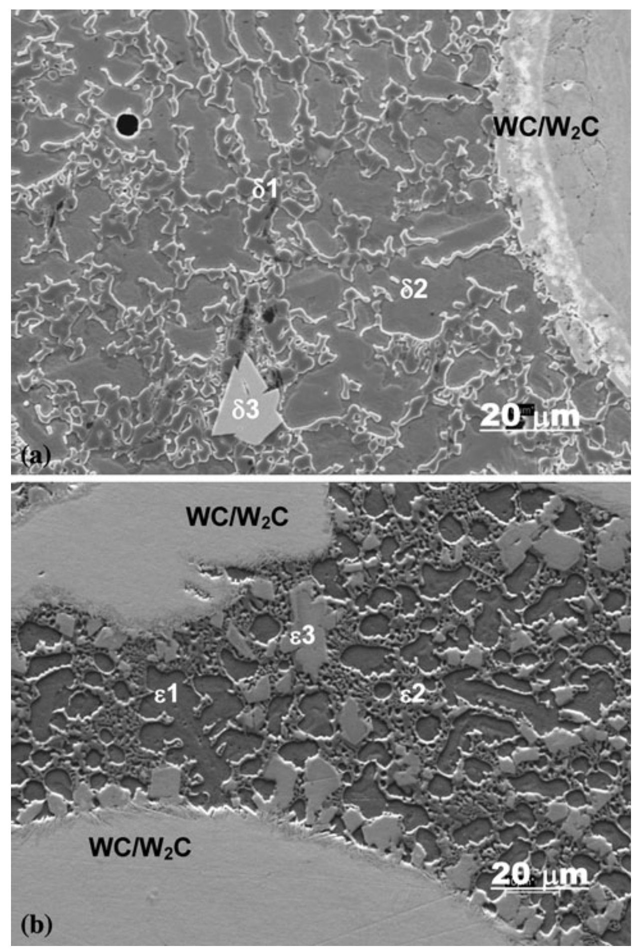

Fig. 3 SEM micrographs of etched surface revealing the typical matrix microstructure of (a) LDSH hardfacing and (b) Commercial C hardfacing

dispersed throughout. DSH and LDSH hardfacings (Fig. 2a, 3a) differed from commercial hardfcings, Commercial A and C, was in a Ni-Si-B phase in the matrix. Ni-11.0B-0.43Si phase was formed in DSH matrix in flame spray and Ni-9.29B-1.11Si phase in laser cladding LDSH. X-ray diffraction revealed Ni_3B in DSH matrix which provided higher thermal conductivity (Ref 9) than other precipitates such CrB, FeB, and Fe_2B and their

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Table 4 Effect of hardfacing chemistry on fluidity

Sample	WC/W_2C, wt.%	Binder, wt.%	WC/W_2C shape	Si + B in binder, wt.%	Fluidity
1	70	30 (Ni-3.39Si-1.78B)	Sphere	5.17	Poor
2	75	25 (Ni-4.56Si-3.27B)	Sphere	7.83	Good
3	80	20 (Ni-4.56Si-3.27B)	Sphere	7.83	Good
4	70	30 (Ni-3.98Si-2.53B)	Sphere	6.51	Good
5	70	30 (Ni-1.0Cr-3.3Si-1.6B-0.75Fe)	Sphere	4.9	Very poor
6	70	30 (Ni-3.39Si-1.78B)	Angular	5.17	Very poor

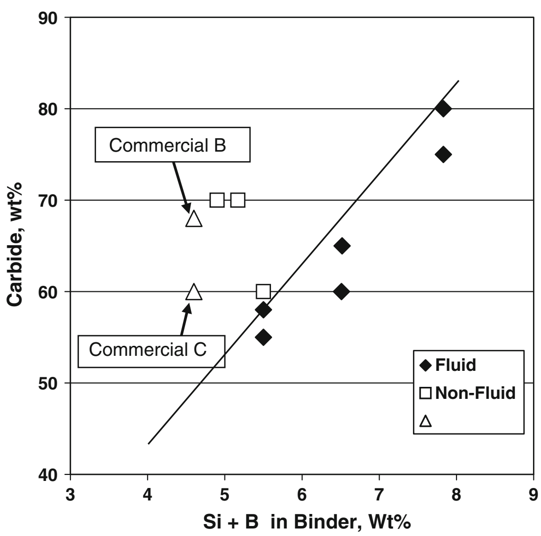

Fig. 4 Effect of Si + B content in binder on fluidity in the spherical cast WC/W_2C and Ni-Si-B hardfacing systems

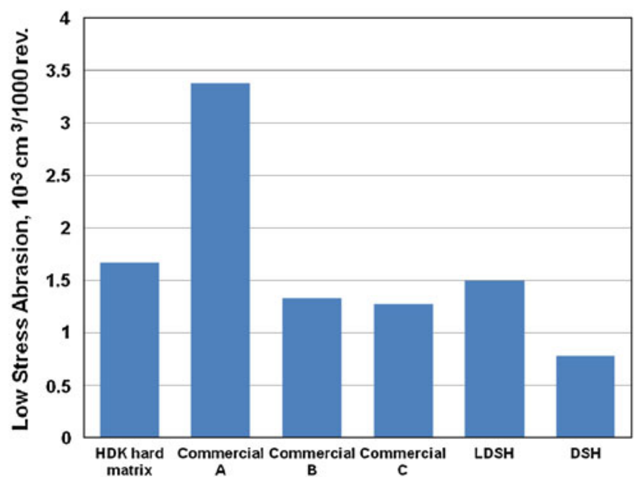

Fig. 5 Low-stress abrasion wear resistance of flame spray DSH and laser cladding LDSH hardfacings compared with commercial hardfacings and HDK hard matrix from PDC matrix drill bit

complex borides as known in the commercial hardfacings. Both Ni-B-Si phases with melting temperature as low as 1010 °C was believed to provide overall toughness to DSH and LDSH hardfacings. Matrix constituency of Commercial A and C hardfacings made them susceptible to cracking during deposition processes.

Fluidity was critical to the quality of the hardfacing, depending on carbide shape, composition, and binder Si + B content in the hardfacing. Low fluidity of the binder alloy resulted in insufficient wetting of binder alloy to the carbide particles during deposition, leading to high porosity and cracks in hardfacing microstructure (Fig. 1c, d). Table 4 gives the chemistry of hardfacings and fluidity in flame spray process. Increasing Si + B content provided greater fluidity to form sound-structure hardfacing for a given carbide size, shape, and content. Qualitatively, higher surface roughness and unevenness of as-deposited hardfacings were indicative of the lower fluidity. Samples #1 and #6 had the same composition except WC/W_2C shapes that influenced their fluidity. In Sample #1, at least 70 vol.% of WC/W_2C was spherical; Sample #6 having angular WC/W_2C exhibited poorer material flow during deposition. The small amount of Fe and Cr additions, <1.0 wt.%, in the binder alloy of Sample #5 showed adverse effect in fluidity of the hardfacing, compared to that of Sample #1. Samples #2 to #4 exhibited that fluidity of the hardfacings increased with increasing Si + B content.

Figure 4 shows effect of Si + B content in the binder on fluidity in spherical cast WC/W_2C and Ni-Si-B hardfacing system. The straight line divides two regions—fluid and non-fluid i.e., sound and unsound hardfacings, based on fluidity during flame spray process. The applicable DSH hardfacing contained at least 40 wt.% spherical cast WC/W_2C, i.e. Si + B greater than 3.5 wt.%; preferably, Si + B range was between 5.5 and 7.2 wt.% for 60-75 wt.% WC/W_2C for high wear and erosion resistances. Two commercial hardfacings using spherical WC/W_2C, which were in non-fluidity region in Fig. 4, were included for comparison. High fluidity via Si + B content in DSH binder system permitted depositing hardfacing with high volume content of WC/W_2C with sound microstructure; up to 80 wt.% was achieved.

The carbide content and binder material in the hardfacing had strong influence on its wear characteristics (Ref 10). Clearly, a DSH hardfacing with higher carbide content yielded greater low- and high-stress abrasion resistances. Sound hardfacing manufacture at given carbide content depended on Si + B content in its binder, as shown in Fig. 4.

Figures 5 and 6 show low-stress wear resistance (ASTM G65 test) and high-stress wear resistance

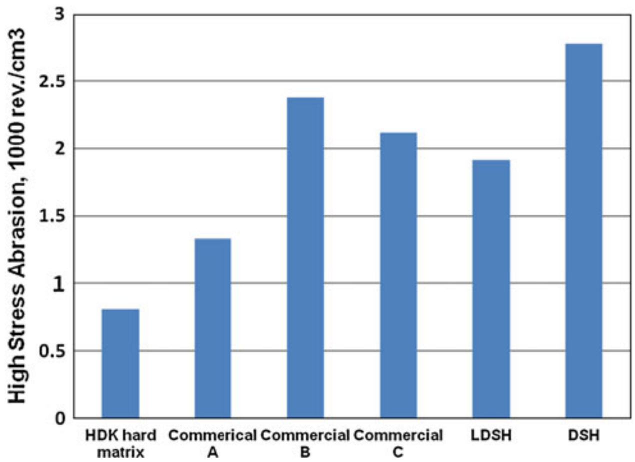

Fig. 6 High-stress abrasion wear resistance of flame spray DSH and laser cladding LDSH hardfacings compared with commercial hardfacings and HDK hard matrix from PDC matrix drill bit

(ASTM B611 test) of DSH and LDSH hardfacings, respectively, compared to commercial hardfacings and HDK hard matrix. HDK hard matrix of PDC matrix drill bit, macrocrystalline tungsten carbide infiltrated with Cu-Ni-Zn-Mn alloy, was also tested to serve as a baseline for comparison. Laser cladding LDSH was comparable to Commercial B and Commercial C, but no cracks were observed. Flame spray DSH was superior to HDK hard matrix, Commercial A, Commercial B and Commercial C in low- and high-stress abrasion. Low dissolution of tungsten carbide in DSH hardfacing, shown in Table 3, explained its favorable wear characteristics as observed in (Ref 5). Expectedly, DSH hardfaced PDC steel bit would outperform Commercial A hardfaced PDC steel bit and PDC matrix bit for wear and erosion protection in a variety of rock formations in drilling application.

4. Field Tests

DSH hardfacing had been applied on new and repaired PDC steel bits for drilling test. Excellent performances of DSH hardfacings were reported. Two case studies revealing wear and erosion characteristics of DSH hardfacing are summarized as follows:

Case Study 1: DSH hardfacing had been used to repair the eroded and worn regions and the webbing between cutters of 14¾ TFX 519 (SN 218034). The bit was run in soft/medium, shale/sand/gumbo formation in the lower gulf coast Texas, USA. DSH hardfacing protected the bit from damages beyond repair (DBR). The bit had drilled eight times in various formations.

Case Study 2: DSH hardfaced 8½″ DS 516 PDC steel bit (SN 221693) had drilled 950 m from the depth 2917 to 3867 m in 427 h in Shahejie group 1-3 formations of claystone and sandstone interbeds at Shengli Oilfield in China. After steel body was repaired and damaged cutters were replaced, the bit drilled 476 m (from 3223 to 3699 m) in 121.8 h in Shahejie lower group 3 formation of interbedded claystone and sandstone in run #2. The dull condition was acceptable for re-run without repair. In run #3, the bit drilled 544 m (from 3302 to 3846 m) in 180.7 h. The compressive strength of these rock formations was 10000-15000 psi. The DSH steel body performed as well as that of the matrix bit in the region.

5. Conclusions

DSH hardfacing has significantly improved wear resistance over commercial hardfacings. In the petroleum drilling field tests, DSH hardfacing has shown excellent performance and durability against wear and erosion; consequently, it has extended bit life up to eight runs. Essentially, DSH is an engineered hardfacing technique that can be tailored to provide steel body bits and tools with ‘‘Matrix-Type Armor’’ for drilling applications.

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References

1. K.C. Antony, Wear-Resistant Cobalt-Base Alloys, *J. Met.*, 1983, **2**, p 52
2. D. Raghu and R. Webber, PTA Proves Its Worth in High-Volume Hardfacing Jobs, *Weld. J.*, 1996, **2**, p 34
3. R. Menon, New Developments in Hardfacing Alloys, *Weld. J.*, 1996, **2**, p 43
4. R.C. Gassmann, Laser Cladding with ($WC + W_2C$)/Co-Cr-C and ($WC + W_2C$)/Ni-B-Si Composites for Enhanced Abrasive Wear Resistance, *Mater. Sci. Technol.*, 1996, **12**, p 691
5. E. Badish and M. Kirchgaßner, Influence of Welding Parameters on Microstructure and Wear Behavior of a Typical NiCrBSi Hardfacing Alloy Reinforced with Tungsten Carbide, *Surf. Coat. Technol.*, 2008, **202**, p 6016
6. A.S.C.M. D'Oliveira, J.J. Tigrinho, and R.R. Takeyama, Coatings Enrichment by Carbide Dissolution, *Surf. Coat. Technol.*, 2008, **202**, p 4660
7. J.M. Amado, M.J. Tobar, J.C. Alvarez, J. Lamas, and A. Yáñez, Laser Cladding of Tungsten Carbides (Spherotene®) and Hardfacing Alloys for the Mining and Mineral Industry, *Appl. Surf. Sci.*, 2009, **255**(10), p 5553
8. T. Marchione, D. Dezert, and A. Choong, The Advancement and Positioning of Laser Cladding in the Surface Engineering Industry, *International Thermal Spray Conference & Exposition, Thermal Spray: Global Solutions for Future Application (DVS-ASM)*, 2010, p 189
9. G.V. Samsonov and I.M. Vinitskii, *Hand Book of Refractory Compounds*, IFI/Plenum, New York, 1980, p 193
10. K. Tsubouchi, M. Akiyama, and T. Okuyama, Development and Optimization of Carbide-Reinforced Tools and Application to Hot Rolling of Stainless Steel, *Trans. ASME*, 1997, **119**, p 687

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