JTTEE5 14:177-182
DOI: 10.1361/10599630523737
1059-9630/$19.00 © ASM International

Thermal Spray and Weld Repair Alloys for the Repair of Cavitation Damage in Turbines and Pumps: A Technical Note

Ashok Kumar, J. Boy, Ray Zatorski, and L.D. Stephenson

(Submitted October 15, 2004; in revised form April 3, 2005)

The cavitation and erosion resistance of 21 thermal spray coatings and four weld repair materials were investigated in the laboratory using cavitation jet and slurry erosion testing. Of the thermal spray coatings, Stellite® 6 deposited by the high velocity oxyfuel (HVOF) process had the lowest cavitation rate (11.7 mg/h). This was higher than the corresponding cavitation rate (3.2mg/h) of 308 stainless steel weld metal currently used as a reference. In the slurry erosion testing, the volume loss of Stellite® 6 applied by the HVOF process was 5.33 cubic mm/h, much lower than the corresponding loss (11.17 cubic mm/h) in the currently used stainless steel 304 reference. Furthermore, the electrochemical potential difference between the carbon steel and HVOF sprayed Stellite 6 coating was 0.25 volts, half the potential difference between the 304 stainless steel carbon steel substrate, and will result in reduced galvanic corrosion of the substrate near the contact areas. Stellite 6 deposited by the HVOF process was recommended for repair of damage resulting from erosion and subsequent cavitation by caused by surface roughening.

Keywords cavitation, corrosion, erosion, thermal spray, weld repair

1. Introduction

The term cavitation refers to the formation and collapse of vapor bubbles or cavities in a fluid, generally due to localized reductions in the dynamic pressure. The collapse of vapor cavities can produce extremely high pressures that frequently damage adjacent surfaces and cause material loss. Cavitation is a major problem for the operation of hydraulic equipment such as hydroelectric turbines, valves and fittings, flow meters, hydrofoils, pumps, and ship propellers (Ref 1) Cavitation frequently contributes to high maintenance and repair costs, revenue lost due to downtime and cost of replacement power, decreased operating efficiencies, and reduction of equipment service life (Ref 2). Pressures greater than 690 MPa (100,000 psi) have been measured in materials by the shock wave from cavitation bubbles (Ref 3). A consensus has developed that material removal by cavitation is caused by a cyclic fatigue process (Ref 4). The pressures can be transmitted from the collapsing bubbles to the surface either in the form of a shock wave or by microjets, depending on the distance from the surface. The cycle of formation and collapse of the bubbles occurs at a high frequency, and the dynamic stress generated can cause the damage of the material by fatigue (Ref 5). The basics of cavitation have been reviewed for the Electric Power Research Institute (EPRI) (Ref 6). Various factors that influence cavitation pitting include velocity effects, material size effects, corrosion, roughness effects, temperature effects, thermodynamic effects, fluid properties, and gas content. Therefore, due to the large number of factors that influence cavitation, qualitative approaches have been developed to assist the plant manager to make cavitation repair decisions. EPRI gives plant owners several options to make cavitation repairs (Ref 6): (a) Make all repairs during each inspection period. Repair only areas where cavitation damage exceeds 3.175 mm (1/8 in.). (b) Repair areas on stainless steel overlays where pitting is 3.175 mm (1/8 in.) or deeper. (c) On carbon steel, repair areas even with light damage using stainless steel weld materials. (d) Allow cavitation to progress to the maximum depth that can be repaired with two weld passes, about 9.525 mm (3/8 in.). The most commonly used method for cavitation repair is the fusion process (i.e., welding). This method involves removing material from the damaged areas and filling the space by welding. The most widely used filler materials are 308L or 309L stainless steel (Ref 7). Extensive weld repair can introduce stresses in the area being repaired and can damage the component. Low, medium, and high cavitation have also been defined in terms of the wear rate for a normal operational year of 8000 h. Low cavitation is defined as 1.587-3.175 mm deep (1/16 to 1/8 in.) damage in carbon steel occurring in two years, medium cavitation is defined as more than 1.587 (1/16 in.) damage in austenitic stainless steel in 1 year; and high cavitation is defined as more than 3.175 mm (1/8 in.) damage in stainless steel in 6 months or less (Ref 8). It should be noted that repair or replacement shall be made whenever cavitation damage threatens the structural integrity of a mechanical component. The cavitation material-loss process usually involves erosion, but erosion may have various causes. For the purposes of this paper, the term

Ashok Kumar, J. Boy, Ray Zatorski, and **L.D. Stephenson,** U.S. Army Construction Engineering Research Laboratory, P.O. Box 9005, Champaign, Illinois 61826-9005. Contact e-mail: Larry.D.Stephenson@erdc.usace.army.mil.

Table 1 Alloy composition, wt.%

Alloy	Co	Cr	Mo	Ni	Mn	Fe	Si	C	W
Tribaloy T-400 (Ref 2)	Balance	8.50	28.5	1.5	…	1.5	2.6	<0.08	…
Tribaloy T-700 (Ref 1)	1.50	15.5	32.5	Balance	…	1.5	3.4	<0.08	…
Tribaloy T-800 (Ref 1)	Balance	17.5	28.5	1.50	…	1.5	3.4	<0.08	…
Stellite 6 (Ref 1)	Balance	28	3	3	…	3	1.1	…	4
SAE 1020	…	…	…	…	0.2	Balance	0.2	0.2	…
430 Stainless Steel	…	14-18	1.0	<0.5	…	Balance	<1.0	<0.12	…
431 Stainless Steel	…	15-17	1.0	1.25-2.5	…	Balance	<1.0	…	…
308 Stainless Steel	…	20	2.0	8.9	…	Balance	0.83	0.04	…
309 Stainless Steel	…	22-24	2.0	12-15	…	…	<1.0	…	…
316 L	…	17	2.5	13	…	Balance	1	0.03	…
Metco 71 VF-NS-1	12	…	…	…	…	1	…	4	Balance
Nistelle C	2.50	16.50	17.00	Balance	…	5.75	1.0	0.12	4.5
Nistelle D	1.50	0.75	…	Balance	…	2.0	9.25	0.12	…
Alloy	**Co**	**WC**							
Sylvania Osram 150A	17	83							
Alloy	**B**	**Cr**	**Mo**	**Ni**		**Fe**	**Si**	**C**	**Cu**
NiCrBSi Alloy	4.0	16.0	3.0	Balance		2.5	4.0	0.05	3.0
Alloy	**Zr**	**Al**		**Ni**					
85-15 Zn–Al	85	15		…					
Ni–5 Al	…	5		95					

Table 2 Composition of advanced iron-based alloys, wt.%

Alloy	Fe	C	Mn	Si	Cr	Ni	Co	N	Mo	P	S
308 Stainless	Balance	0.04	1.7	0.83	20	8.9	…	0.05	…	…	…
Ireca	Balance	0.3	10	3	17	…	10	0.1	…	…	…
Hydroloy 913	Balance	0.2	10	3	17	…	10	0.2	…	…	…
Hydroloy 914	Balance	0.22	10	4.6	17	2.0	10	0.3	…	…	…
NOREM Powder	Balance	1.17	12.2	5.1	25.3	8.2	…	0.22	1.8	0.03	0.01
NOREM Wire	Balance	1.19	6.0	4.1	25.3	4.6	…	0.11	1.2	0.008	0.006
CaviTec	Proprietary austenitic stainless steel										
D-CAV	Proprietary austenitic stainless, cobalt free										

"erosion" will refer specifically to slurry erosion, which occurs at a surface impinged upon by solid particles suspended in a liquid stream.

1.1 Materials Selection

Stainless steels are the most commonly used materials for cavitation repair. The detailed compositions of these and other materials are shown in Tables 1 and 2.

Some of these alloys are now available in powder form suitable for application by high-velocity oxyfuel (HVOF) or plasma spray processes. Based on results from literature reviews, materials were selected for evaluation and testing as thermal sprayed coatings applied either by HVOF or plasma spray processes. Literature review indicated that Tribaloy T-400 applied by HVOF had an impeding effect on the cavitation of substrate (Ref 9); therefore, other similar hardfacing alloys were also selected. The list of cavitation repair materials that can be thermally sprayed by high-velocity and plasma processes includes hard facing alloys based on cobalt [Stellite 6 (Stellite Coating Company, Goshen, IN), Tribaloy T-400, and Tribaloy T-800] and tungsten-carbide-based alloys [Metco 71 VF-NS-1 (Metco, Westbury, NY), and Sylvania Osram 150 A (Sylvania Osram, Danvers, MA)]. Bulk and welded cobalt-based Stellite 6 have lower cavitation rates compared with 308 stainless steel (Ref 10, 11). Other cobalt-based hard facing alloys include Tribaloy T-400 and Tribaloy T-800, which contain 8-17% Cr and 28% Mo, in contrast to the Stellite 6, which has 28% Cr and 3% Mo (Table 1). The characteristic high hardness and wear resistance of thermal sprayed WC-Co materials have made them the material of choice for use as protective coatings in a variety of industrial applications.

The coatings selected for the initial screening were Metco 71 VF-NS-1 and Tribaloy T-800 by plasma spray; and Tribaloy T-400, Tribaloy T-800, Stellite 6, and Sylvania Osram 150A by HVOF process. As the project progressed, additional materials were prepared and tested.

2. Experimental Procedures

2.1 Sample Preparation

2.1.1 Thermal Sprayed Samples. The plasma spray equipment used was a 9 MB gun from Sulzer Metco, Inc., Westbury, NY. Argon was the primary gas and a Plasma Technic Twin 10 was the powder feeder. The HVOF equipment was a Jet Kote 2 system from Stellite Coating Co., Goshen, IN. Thermal spray coatings were produced by State University of New York (SUNY) for ultrasonic cavitation screening.

The coatings were applied by plasma spray and HVOF methods onto mild steel plates. The panels were SAE6 1020 cold-rolled steel, 2.54 mm (0.10 in.) thick sheared to approximately 15.875 × 15.875 mm (0.625 × 0.625 in.) The panels were cleaned with acetone or alcohol and roughened by grit blasting. The initial grit blast was performed with 60 aluminum oxide grit at 0.413 MPa (60 psi) using a suction-type grit blast cabinet. Coating delamination was observed during testing on many of the samples, which was attributed both to edge effects due to small sample size and inadequate surface roughness of the substrates. To alleviate this problem, 45° chamfers of approximately 15.875 mm (0.625 in.) were ground into the edges of the panels; after cleaning, the panels were grit blasted with 24 grit aluminum oxide at 0.551-0.689 MPa (80-100 psi). This produced a surface roughness of at least 0.00762 mm (300 micro inches) Ra using a 0.762 mm (0.030 in.) waviness cutoff with a 2.54 mm (0.100 in.) travel as measured using a Mitutoyo Surftest III surface profilometer (Mitutoyo Corp., Aurora, IL). This corresponds to a surface profile of between 0.0254 and 0.0508 mm (0.001-0.002 in.). No further delamination was observed on panels prepared in this way. The spray coatings were deposited within 4 h after the grit blasting. If more than 4 h passed, the samples or substrates were grit blasted again before coating.

2.1.2 Advanced Weld Material Samples. Weld samples of CaviTec and Hydroloy 914 were prepared. Carbon steel plate 1/4 in. thick was welded with CaviTec and Hydroloy 914 flux-core filler metal. A uniform single layer was deposited on the plate in the flat position with a gas metal arc welding (GMAW) system. The shield gas was argon and the welding parameters were those recommended by the wire manufacturer. For the CaviTec, the welding current was 125 A, and the voltage was 30 V. For the Hydroloy 914, the welding current was in the range 100-140 A, and the voltage was in the range of 16-18 V. The samples of Norem and D-Cav were prepared by the manufacturers using the GMAW process.

2.3 Cavitating Jet Testing

There are three principal laboratory testing techniques to determine cavitation rates: ultrasonic vibratory cavitation testing, venturi cavitation testing, and cavitating jet testing. The ultrasonic vibratory cavitation testing method was found to be unable to produce in the laboratory the same type of adhesion failures for coatings that have been observed under field conditions. Further details of the research described in this paper may be found in the U.S. Army Construction Engineering Research Laboratory (USACERL) Construction Productivity Advancement Research (CPAR) Report, entitled "Cavitation- and Erosion-Resistant Thermal Spray Coatings" (Ref 12). The cavitating jet testing method uses a submerged cavitating jet to erode a test specimen placed in the jet's path (Fig. 1). Water is supplied through a cartridge-style filter to a positive-displacement pump rated at 68.9 MPa (10,000 psi) and operated at 27.6 and 41.4 MPa (4000 and 6000 psi) in the current tests. The pump discharge is connected with high-pressure stainless steel piping to the stainless steel test chamber, which is approximately 45.72 cm wide, 45.72 cm long, and 45.72 cm deep (18 × 18 × 18 in.). Transparent windows are provided for observation of the specimen. A safety interlock on the test chamber lid prevents activation of the pump when the test chamber is open.

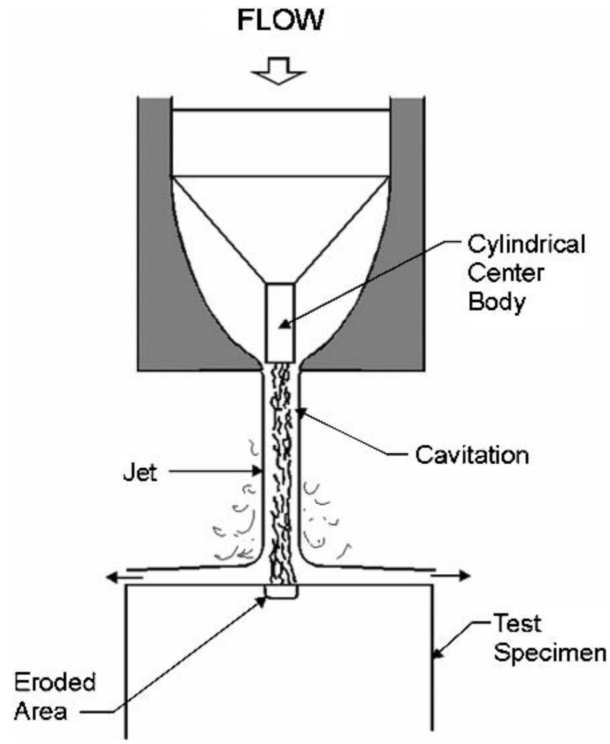

Fig. 1 Schematic diagram of cavitating jet testing apparatus (Ref 2)

The test chamber includes an adjustable specimen holder and an adjustable nozzle. The nozzle contains an internal centerbody. Flow downstream from this centerbody and the low pressure associated with the high-velocity jet produce a central region of intense cavitation that is channeled by the jet onto the test specimen. Three cavitation tests were conducted on each sample at the Tennessee Valley Authority (TVA) Engineering Laboratory, at Norris, TN, and the results were averaged. The relative cavitation rate, referenced to a standard material, provides a good method for comparing materials that have a wide range of properties (Ref 10). Weld materials that had higher cavitation resistance compared with welded stainless steel in the laboratory also performed better than stainless steel in the field (Ref 13). The cavitating jet laboratory test results for weld alloys were found to correlate well with field experience (Ref 14).

2.4 Erosion Testing

A slurry wear test developed by the U.S. Bureau of Mines was used to determine the wear rate of thermal sprayed coatings deposited by both the plasma spray and HVOF processes (Madson 1990) (Ref 15). Samples of Stellite 6, Tribaloy T-400, and Tribaloy T-800 along with control samples of 304 stainless steel, and ASTM A 572 (Ref 16) carbon steel were tested in the slurry wear apparatus. All samples were cleaned and weighed before insertion into the test apparatus. Each specimen was electrically isolated (to eliminate galvanic corrosion effects) from the other samples by using ultrahigh molecular weight (UHMW) polyethylene specimen blanks. The slurry erosion test consisted of running 2 wt.% silica sand slurry through the specimen chamber of the slurry wear apparatus. The impeller turned at 2256 revolutions per minutes (rpm), which yielded a nominal slurry velocity

Table 3 Results of cavitating jet testing of HVOF coatings at 27.6 MPa (4000 psi)

Sample	Weight loss, mg/h	Cavitation rate vs. 308 weld
308 Stainless Steel-Weld	3.2	1.00
Stellite 6	11.7	3.6
NOREM	16.9	5.3
Tribaloy T-400	18.9	5.9
Tribaloy T-800	23.8	7.4
WC/Co (Metco 71 VF-NS-1)	35.3	11.0
WC/Co (Sylvania Osram 150A)	49.0	15.3

of 15.6 m/s. The test was set up to be a single pass test, i.e., the slurry was not recirculated. The temperature of the water was 11 °C. The test was interrupted at 10, 30, and 60 min to clean and weigh the test specimen. The change in weight was determined and converted to a linear erosion rate based on the density of the material. For the thermal spray coatings, a density of 95% of the theoretical density was used in the calculations to determine volume loss.

3. Results and Discussion

3.1 Cavitating Jet Test Results

Coatings prepared by HVOF, plasma spray, and other thermal spray techniques were tested at 27.6 MPa (4000 psi) using the cavitating jet apparatus. These test results are shown in Table 3. Weld alloys were tested by a similar technique at 27.6-41.4 MPa (4000 and 6000 psi), as shown in Table 4.

The cavitation rates of all coatings prepared either by the HVOF or plasma spray processes were higher than the welded 308 stainless steel reference. The best-performing coating material prepared either by HVOF or plasma spray was Stellite 6, with a cavitation rate of 11.7 mg/h (HVOF) and 13.6 mg/h (plasma sprayed). The HVOF coatings generally had lower cavitation rates than the plasma spray coatings. This is consistent with the results of other researchers (Ref 17, 18). Based on the cavitation testing results reported here and by other researchers, the cavitation rate of carbon steel is between 1.6 and 2.0 times higher than the cavitation rate of the welded 308 stainless steel reference. The cavitation rate of Stellite 6 applied by the HVOF process was 3.6 times higher than the cavitation rate of the welded 308 stainless steel reference. Only two materials prepared by combustion flame spray process survived the cavitation jet test. These were the NiCrBSi alloy and 316 stainless steel. Both had significantly higher cavitation rates than the welded stainless steel reference material. All other materials prepared by combustion flame spray and the two-wire arc processes failed due to delamination of the coating during testing. This includes CaviTec, a wire designed for use in transferred arc welding but applied using a two-wire arc thermal spray system in this test. Samples of advanced iron-based weld alloys were prepared and tested using the cavitating jet apparatus at both 27.6 and 41.4 MPa (4000 and 6000 psi.). The advanced weld alloys showed superior cavitation resistance compared with welded 308 stainless steel. The cavitation rates at 27.6 MPa (4000 psi) ranged from 1.0 mg/h for NOREM to 2.6 mg/h per for CaviTec. All materials performed very well and had cavitation rates lower than the 308 stainless steel reference panel (3.2 mg/h). As noted

Table 4 Results of cavitating jet testing of weld alloys

Alloy	Weight loss, mg/h	Test pressure, MPa	Cavitation rate vs. 308 weld
308 Stainless Steel	3.2	27.6	1.0
NOREM	1.0	27.6	0.3
D-CAV	1.3	27.6	0.4
Hydroloy 914 Sample A	1.7	27.6	0.5
Hydroloy 914 Sample B	2.0	27.6	0.6
CaviTec Sample A	2.3	27.6	0.7
CaviTec Sample B	2.6	27.6	0.8
CaviTec Sample A	3.1	41.4	0.2
CaviTec Sample B	3.4	41.4	0.3
D-CAV	3.4	41.4	0.3
Hydroloy 914	3.5	41.4	0.3
NOREM	4.3	41.4	0.3

above, cavitation rates also were measured at a test pressure of 41.4 MPa (6000 psi). Due to the use of different nozzles, there was variation in values of the stainless steel in different tests at 41.4 MPa (6000 psi). This required the results be normalized to the 308 stainless steel reference samples tested at the same time. At the 41.4 MPa (6000 psi) test pressure, the cavitation rates were higher than at 27.6 MPa (4000 psi), ranging from 3.1 to 4.3 mg/h. All of the materials tested performed very well, with cavitation rates only 0.2-0.3 times that of the welded 308 stainless steel reference samples. The tests were not able to identify significant differences between these advanced weld alloys; a larger number of samples would be required to establish statistical variation and ranking. The end user's choice of one material over another would depend on additional factors such as field weldability and cost.

3.2 Erosion Results

The results of the slurry erosion wear test are presented in Table 5. The results show that three thermal spray coatings applied by the HVOF process performed better than the carbon steels [ASTM A572 (Ref 17), ASTM A514 (Ref 19), AISI 4340)] and the stainless steel reference materials. The slurry erosion rate for stainless steels ranged from 9.2 to 11.5 mm^3. The HVOF coating with the lowest volume loss after 1 h was WC-12Co, with 1.06 mm^3. The volume loss after 1 h for the Stellite 6 and Tribaloy T-800 coatings were 5.33 and 6.76 mm^3, respectively. This loss is lower than the 1-h volume loss of 19.70 mm^3 for ASTM A572 (Ref 17), 12.36 mm^3 for ASTM A514 (Ref 20), 11.7 mm^3 for 304 stainless steel, and 7.82 mm^3 for AISI 4540. The Tribaloy T-400 and Tribaloy T-800 coatings applied by plasma spray did not perform as well as the reference alloys. Visual inspection of the Tribaloy T-800 prepared by plasma spray, after 1 h of slurry erosion wear testing, showed penetration of the coating and wear of the substrate. Therefore, HVOF coatings may be considered for use in hydraulic equipment to protect against erosion.

3.3 Galvanic Corrosion Results

Cavitation may combine with corrosion to create much greater damage rates than the sum of the two alone. Metals usually develop passive films or layers on the surface that inhibit further corrosion and metal removal. However, cavitation removes the passive film, thus exposing a fresh metal surface that

Table 5 Results of slurry erosion wear test

Material	Process	Theoretical density cast, gm/cm^3	Average mass loss 10 min, mg	Average mass loss 30 min, mg	Average mass loss 60 min, mg	Standard deviation mass loss 60 min, mg	Average volume loss 60 min, mm^3	Relative volume loss vs. ASTM A 572
ASTM A572	Cast	7.80	24.0	75.9	153.7	8.1	19.70	1.0
ASTM A514	Cast	7.85	16.0	48.4	97.0	8.4	12.36	0.6
AISI 4340	Cast	7.81	11.2	32.2	61.1	7.1	7.82	0.4
304 Stainless Steel	Wrought alloy	7.91	14.7	41.6	88.4	6.0	11.17	0.6
316 Stainless Steel	Wrought alloy	7.91	14.1	39.9	75.2	1.4	9.50	0.48
308 Stainless Steel	Weld overlay	7.91	12.2	37.7	73.0	11.5	9.22	0.46
310 Stainless Steel	Weld overlay	7.91	14.0	44.8	8.37	16.0	10.58	0.53
Tribaloy T-400	Plasma spray	9.00	28.6	77.8	144.9	1.9	16.95	0.9
Tribaloy T-800	Plasma spray	8.65	49.4(a)	121.1(a)	27.2(a)	65.4(a)	27.2(a)	1.4
Tribaloy T-400	HVOF	9.00	19.6	60.1	114.5	109	13.39	0.7
Tribaloy T-800	HVOF	8.65	13.8	32.8	55.6	10.7	6.76	0.3
Stellite 6	HVOF	8.38	7.7	23.0	42.5	2.4	5.33	0.3
WC-12Co	HVOF	13.2	3.7	7.4	13.3	1.6	1.06	0.13

(a) Coating was completely penetrated.

can readily corrode. The increased surface roughness caused by corrosion may also promote cavitation (Ref 5). Published results show that cobalt wear-resistant alloys undergo little attack in mine water, sea water, or boiler water at temperatures typical for those environments. After two years in sea water, wear-resistant cobalt alloys have shown a corrosion rate of about 0.00254 mm (0.0001 in.) per year, with maximum pitting of 0.01778 mm (0.0007 in.). This rate is only 2% of the corrosion rate of mild steel in sea water, which occurs at about 0.127 mm per year (0.005 in. per year) (Ref 21). Stainless steel weld repair of mild carbon steel surfaces results in the formation of an interface between the mild carbon and the stainless steel. These two steels have different electrochemical potentials causing galvanic corrosion of the carbon steel. The damage to the carbon steel is usually repaired by welding more stainless steel. In some cases, entire throat rings have required stainless steel weld repair. Complete fusion welding of stainless steel overlay on the throat ring can produce thermal stresses on cooling. These thermal stresses cause the weld overlay and liner to pull away from the concrete support. The detached steel liner is subject to buckling and damage. To prevent this disbonding, anchors and grout are used, otherwise the steel liner would be overstressed. The thermal shrinkage stresses for thermal spray coatings are much lower than that from welding because the coatings are much thinner than the weld materials and thermal spray introduces less heat to the substrate than welding. Using thermal spray coatings on the entire throat ring or discharge tube liner would prevent the corrosion, erosion, and cavitation damage to the substrate and eliminate the need for extensive weld repair. Measurements of the electrochemical potential of 304 stainless steel, ASTM A572 (Ref 17) carbon steel and ASTM A36 (Ref 20) carbon steel were made relative to a copper-copper sulfate reference electrode in tap water. The electrical conductivity of the tap water was 325 microsiemens (corresponding to a resistivity of 3075 ohm cm). The electrochemical potential differences between Stellite 6 coated specimens and both ASTM A572 (Ref 17) and A36 (Ref 20) carbon steels in tap water were 0.25 V, i.e., half the potential differences (0.5 V) between 304 stainless steel and both ASTM A572 (Ref 17) and A36 (Ref 20) carbon steels. Therefore, Stellite 6 would reduce the galvanic corrosion problem due to the smaller electrical potential difference. However if the interface corrosion between the stainless steel and carbon steel is shifted to the Stellite 6-carbon steel interface, then complete coverage by thermal spray coatings may be required.

4. Summary

The thermal spray coatings deposited by the HVOF process exhibited lower cavitation wear rates than the thermal spray coatings deposited by the plasma spray process, as determined by laboratory testing using the cavitating jet test apparatus. Of the 21 thermal spray coatings tested in the laboratory using the cavitating jet apparatus, the lowest cavitation rate was for Stellite 6 as applied by the HVOF thermal spray process. The cavitation rate of Stellite 6 was 11.7 mg/h, while the corresponding cavitation rate for 308 stainless steel weld metal was 3.2 mg/h. Thermal spray coatings were applied to stainless steel weld-repaired substrates and carbon steel substrates. The cavitation rates of advanced weld metal overlays, such as NOREM, D-CAV, CaviTec, and Hydroloy 914, ranged from 1.0 to 2.6 mg/h, which were lower than the corresponding cavitation rate for standard 308 stainless steel weld metal (3.2 mg/h). In slurry erosion wear testing, the volume loss for Stellite 6 coatings deposited by the HVOF process was 5.33 mm^3/h, less than half the volume loss of 11.17 mm^3/h for 304 stainless steel. The corresponding loss for ASTM A572 carbon steel was 19.70 mm^3/h. The electrochemical potential differences between Stellite 6 coated specimens and both ASTM A572 and A36 carbon steels in tap water were 0.25 V, half the potential difference between 304 stainless steel and mild carbon steel (i.e., 0.50 V). Stellite 6 coatings deposited by the HVOF process over surfaces having dissimilar metals (i.e., stainless steel weld repair adjacent to the mild steel base metal) will mitigate the corrosion activity at the dissimilar metal boundary due to its superior corrosion resistance as compared with the carbon steel substrate material.

Acknowledgment

This work was conducted under the Construction Productivity Advancement Research (CPAR) Program and was published in USACERL Report 97/118 dated July 1997.

References

1. A. Kumar, Exotic Alloys for Cavitation Resistance: Passing the Tests, *Hydro Review,* Vol 17 (No. 5), 1998, p 16-21
2. P. March and J. Hubble, "Evaluation of Relative Cavitation Erosion Rates For Base Materials, Weld Overlays, and Coatings," Report No. WR28-1-900-282, Tennessee Valley Authority Engineering Laboratory, Norris, TN, September 1996
3. B. Vyas and C.M. Preece, Stress Produced in a Solid by Cavitation, *J. Appl. Phys.,* Vol 47, 1976, p 5133-5138
4. R.H. Richman and W.P. McNaughton, Correlation of Cavitation-Erosion Behavior with Mechanical Properties of Metals, *Wear,* Vol. 140, 1990, p 63-82
5. R. Schwetzke and H. Kreye, Cavitation Erosion of HVOF Coatings, Thermal Spray: Practical Solutions for Engineering Problems, C.C. Berndt, Ed., ASM International, 1996, p 153-158
6. P.R. Rodrigue, "Cavitation Pitting Mitigation in Hydraulic Turbines," Vol. 1&2, Final Report EPRIAP-4719 Project 1745-10, Electric Power Research Institute, Palo Alto, CA, August 1986
7. R. Richard, P. Willis, and A. Kumar, "Application of Thermal Spray and Ceramic Coatings and Reinforced Epoxy for Cavitation Damage Repair of Hydroelectric Turbines," TR FM-93/01, USACERL, Champaign, IL, March 1993
8. T. Spicher, *Hydro Wheels: A Guide to Mantaining and Improving Hydro Units,* HCI Publications, Kansas City, MO, 1995
9. "Standard Test Method for Cavitation Erosion Using a Vibratory Apparatus," G32, ASTM, 1992
10. "Adhesion or Cohesive Strength of Flame-Sprayed Coatings," C633, ASTM, 1992
11. A.D. Althouse, C.H. Turnquist, and W.A. Bowditch, *Modern Welding,* The Goodhearted Wilcox Co., Homewood, IL, January 1994
12. "Standard Practice for Liquid Impingement Erosion Testing," G73, ASTM, 1992
13. J.S. Baker, "Cavitation Resistant Properties of Coating Systems Tested on a Venturi Cavitation Testing Machine," Bureau of Reclamation, Research Laboratory and Services Division, Denver, CO, January 1994
14. O.F. Karr, J.B. Brooks, P.A. March, and J.M. Epps, Raccoon Mountain Pumped Storage Plant, Unit 3 Weld Overlay Field Test Inspection Report, Tennessee Valley Authority Report No. TVA/PBO/R&D-90/4, May 1990
15. B.W. Madson, *Corrosion Wear,* Metals Handbook, 10th ed., Vol. 18, ASM International, 1990, p 272-279
16. "High-Yield Strength Low Alloy Columbium Vanadium Structural Steel," A572, ASTM, 2001.
17. C.L. Cheng, C.T. Webster, and J.Y. Wong, "Reduction of Cavitation Erosion Damage on Hydraulic Structures through the Use of Coatings," Canadian Electrical Association, Montreal, Quebec, Report CEA No. 511G530, May 1987.
18. P. Crook, *Cobalt and Cobalt Alloys,* Metals Handbook, 10th ed., Vol 2, ASM International, p 447-454
19. "High-Yield Strength Quenched and Tempered Steel Plate, Suitable for Welding," A514, ASTM, 2001
20. "Standard Spec. for Carbon Structural Steel," A36, ASTM, 2001
21. M.G. Fontana and N.D. Green, *Corrosion Engineering,* 2nd ed., Vol 2, ASM International, p 447-454