Potential of High Velocity Oxy Fuel Thermal Spraying in Turbine Shaft Repairing

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Abstract: In this paper, the application of thermal spray coatings in high speed shafts by a revolution up to 23000 RPM has been studied. The agglomerated WC-12Co powder was coated on gas compressor components using high velocity oxy fuel (HVOF) method and its microstructure and residual stress were evaluated. Two high speed shafts were coated using the experimental data and the results demonstrated an acceptable performance in the high cycles. The results have shown that the developed coating has 148±30 MPa using hole drilling method and 156-257 MPa compressive residual stresses in curvature method. Morphological and crystallographical studies were conducted using optical microscopy, scanning electron microscopy (SEM) and X-ray diffraction respectively to evaluate the powder and coating characteristics.

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1. Introduction

Thermal spray is a promising method replacing the hazardous chrome plating in the finishing industry. This method has demonstrated to have superior wear and fatigue properties when compared to hard chromium using cermets e.g. tungsten carbide-cobalt (WC-Co). High velocity oxy fuel (HVOF) coatings have exhibited wear resistant WC-Co coating with high density; superior bond strength and less decarburization than many other thermal spray methods. This is attributed to its high particle impact velocities and relative low peak particle temperature [1],[2]. The main challenge remains on control of residual stress imposed primarily by quenching (fast cooling from melting point to substrate temperature) which is of tensile nature and secondary by the difference in the thermal expansion coefficients between the coating (αc) and substrate (αs), which leads to residual stresses induced by the mismatch of thermal shrinkage during cooling from the process temperature to room temperature, during the so called secondary cooling]. The high velocity impact of semimolten particles on the substrate in the HVOF spray process is revealed as peening stress which is of compressive nature. The final total residual stress through the whole coating/substrate system which directly affects its bonding strength is the sum of the above mentioned stresses together with the compressive stress state of the substrate induced during the grit blasting prior to spraying [3]. One of the concerns in thermal spray process is determining the residual stress. The level of this stress and its sign has a significant effect on coating performance. A number of techniques have been used in the past decades to measure residual stresses in thermal spray coatings. Curvature measurement methods rely on the monitoring of changes in component distortion, either during deposition or after. Diffraction methods are based on the elastic deformations within a polycrystalline material to measure internal stresses in coatings. The stresses cause deformation i.e., changes in the distance between the lattices, which are used as internal strain gages. Shifts in diffraction peaks are recorded from which the strain distribution is calculated. Diffraction methods are based on the elastic deformations within a polycrystalline material to measure internal stresses in coatings. The stresses cause deformation i.e., changes in the distance between the lattices, which are used as internal strain gages. Shifts in diffraction peaks are recorded from which the strain distribution is calculated [2], [3].

In this study mechanical property of coating in high speed gas compressor shafts (up to23000 rpm) using high velocity oxy fuel thermal spray method has been investigated. This coating was developed based on pre-studied standard experiments (fatigue, bond strength, and residual stress); Morphological and crystallographical studies were conducted using optical microscopy, scanning electron microscopy (SEM) and X-ray diffraction respectively to evaluate the powder and coating characteristics.

2. Material and Methods

AISI 1045 steel substrate samples were industrially coated using HVOF gun (Metjet III, Metallization). Before deposition, substrate was grit blasted with SiC particles (16µm mesh) and ultrasonically cleaned in acetone. The WC-12Co particle size was between 15-40µm. The spray parameters are according to Table1. The remained parameters were indicated by the company. In the as deposited condition, the coating had an average roughness of ~4 µm. Residual stress evaluation by curvature and hole drilling (ASTME837) method was investigated on $120\times20\times1.2mm^3$ and $\phi20\times10mm$ samples respectively. Furthermore fatigue and bonding strength evaluations were conducted on samples prepared according to ASTM E466 and ASTMC633 respectively**.** The samples were evaluated in as spray condition. The microhardness indentation procedure used is given in the relevant ASTME384-10 Standard .Through thickness microhardness profile obtained from the Vickers hardness machine in 2.94N load. The average coating porosity also has been considered. The porosity analysis was determined by optical image analysis. Two gas compressor shafts (23000 rpm, charge and discharge) were evaluated using HVOF thermal spray (Fig.1).

Table 1: Thermal spraying parameters

Fuel rate (ml/min)	250
Oxygen rate (l/min)	830
Spray distance (mm)	340± 10
Spray angle (deg)	90

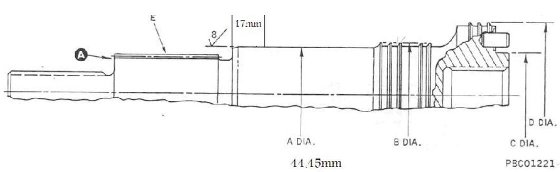

Fig. 1: Gas compressor shaft (subjected workpiece)

3. Results and discussion

Standard Mechanical Tests, microhardness test, XRD, SEM, image analysis were performed to evaluate the wear mechanisms and crystalline structure phases, morphological and porous structure of the WC-12Co powder and its coating respectively.

3.1 wear mechanisms

Fig.2 shows the scanning electron microscopy image of the worn surface in shaft – bearing contact zone. The microplaughs at the worn surface are seen apparently. The wear mechanism is seamed to be abrasion wear. The abrasion wear resistance is enhanced by applying a hard coating such as WC-Co cermets.

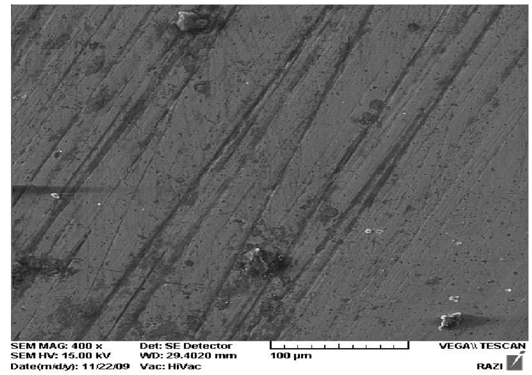

Fig 2: SEM topography of worn shaft surface

3.2 Crystallographic characterization

XRD analysis was performed to evaluate the crystalline structure phases of the WC-12Co powder coating. The patterns correspond to presence of WC, W_2C and W_6Co_6C. The presence of W_2C and W_6Co_6C are thought to be due to decomposition of WC at high temperature of flame jet and abundant amount of oxygen when the powders are accelerated. Decarburization of WC has been reported in the literature to affect the coating hardness and wear resistance [2]. In the work of Stewart et al. [4], it has been established that the formation of W_2C upon splat quenching is caused by dissolution of WC in Co matrix whereas the formation of elementary W depended on the composition of the starting powder. Yang et al. [5] showed that larger degree of WC decomposition is correlated to a smaller carbide grain size in the starting powder. Other forms of W-Co-C may also be present in the matrix in the form of $W_xCo_yC_z$ which are not detected by the XRD method due to their low content or high dispersion in the coating.

3.3 Morphological characterization

Fig. 3 illustrates the Scanning Electron Microscopy (SEM) morphology of agglomerated WC-12Co powder in two magnifications. As observed the particles are spherical and uniformly distributed (15-45 µm) with high porosity. Fig.4 shows the SEM topography of the coating at the free surface. As illustrated the coating has an agglomerated morphology consisting of WC-Co. The agglomerates can be clearly seen. The microstructure consists of a network of WC-Co agglomerates. WC-Co agglomerates are formed where WC particles are dispersed in Co matrix resulting in high peripheral porosity as a result of WC particle moving towards the centre of agglomerates. This can be clearly observed in the micrograph. The porosity is thought to be intrinsic phenomena in thermal spray coating because of process nature which must be limited by controlling the process parameters. Fig. 5 illustrates a general view of the coating after metallographic preparation. The WC-12Co HVOF thermally sprayed coating appear to be quiet dense. The porosity analysis determined by optical microscopy and image analysis shows apparent porosity less than 1%.The presence of lamella boundaries, pores and well distribution of WC grains of different size embedded in the Co matrix is apparent.

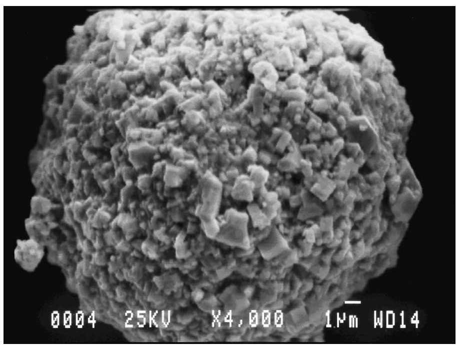

Fig.3: Particle morphology in 4000x magnification

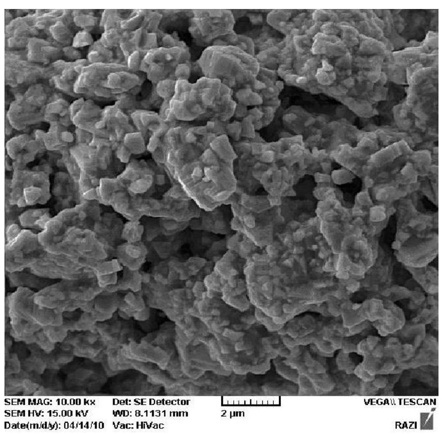

Fig.4: SEM topography coating surface

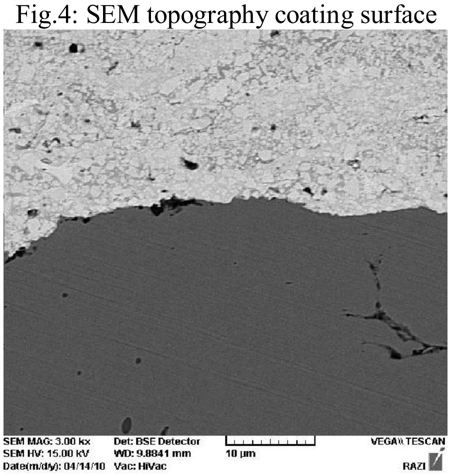

Fig.5: SEM micrograph of substrate-coating interface

3.4 Microhardness characterization

The measuring is done using an eyepiece micrometer. Hardness is calculated according to the following formula:

$$HV = \frac{F(Kgf)}{A(mm^2)} = \frac{2F\sin(\alpha/2)}{d^2} \times 1000$$
$$= 1854\frac{F}{d^2}$$

where F is the test load and A is surface area of indentation. The angle between faces on the Vickers' diamond is 136°.

The hardness is not uniform through the coating thickness and in 0.3 mm the hardness is in maximum value (1397HV). For this cemented carbide thermal spray coating, the average of measured hardness numbers was 1166 HV. The wear resistance of thermally sprayed WC-12Co coating is attributed to be due to high hardness of these coatings.

3.5 Residual stress

3.5.1 Curvature method

The Stony equation [6] is used to obtain the relationship the residual stress and the curvature [7]:

$$\sigma_r = -\frac{kE_s t_s^2}{6(1-\nu_s)t_c}$$

Which the k (=1/R) represent the final curvature, t_s substrate thickness, t_c coating thickness. E_s and ν_s are the elastic modulus and Poisson ratio of substrate respectively. Residual stress evaluation was performed using post-mortem curvature method on appropriate samples. Stoney's equation was used for this purpose. Three different thicknesses was thermally sprayed on the AISI 1045 steels samples (350±20 µm, 650±20 µm and 980±20 µm). The curvature of coated strip was measured by using Coordinate Measurement Machine (CMM). Stony's equation parameters are given in table2. The Superposition of residual stresses with tensile and compression natures are evaluated to be compressive. The mean value estimated for residual stress is presented in Fig.6. As it can be seen from the results, as the thickness is increased the compressive residual stress is reduced.

Table2: Stony's equation parameters in this study

Sample	R(mm)	E_s(GPa)	ν_s	t_c(mm)	t_s(mm)
1	1250	210	0.3	0.35	1.2
2	915	210	0.3	0.65	1.2
3	735	210	0.3	0.98	1.2

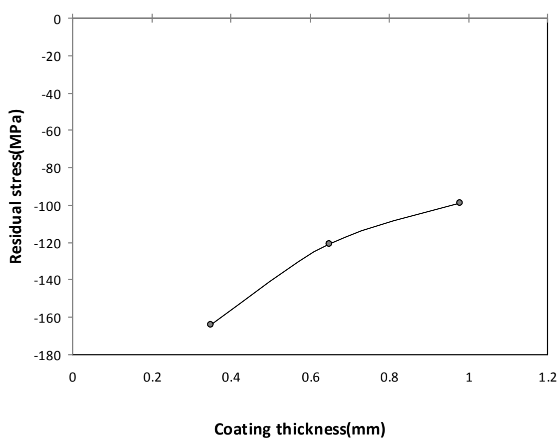

Fig.6: Compressive Residual stress from curvature method

3.5.2 Hole drilling method

In the present work, through-thickness residual stresses were determined up to depths of 500 µm, for the coatings of 350 µm thickness by hole drilling method and rosette strain gages. The parameters E=330 MPa and ν=0.3 were employed for computing the calibration curves required by the integral method. The residual stress distribution for the WC–12Co deposit shows that the stress is not uniform through the thickness. Both the σmax and σmin in this coating are compressive. The von misses effective stress calculated to be 148±30 MPa which is closed to results of Santana investigation [2].

3.6 Case Study

Two gas compressor shafts (23000 rpm, charge and discharge) were evaluated using HVOF thermal spray as described. The coated shafts with 0.35mm thickness were ground in order to achieve uniform thickness of 160 µm. The roughness of as ground coating was ~0.2 µm. The filed study has revealed that one of the coated shafts (charged) failed after 7800 hr at 23000 rpm (Fig. 7) demonstrating high wear resistance in contact zone with journal and high adhesive and cohesive strength and the later (discharge) still holds after 7800 hr at 23000 rpm. The failure is thought to be due to fatigue crack initiated from the rough substrate surface. Fig. 8 illustrates a general view of the coating after metallographic preparation. The cleaning of substrate surface after grit blasting is of great importance. The SiC particle that has reminded from sand blasting process is shown. This particle may cause fatigue failure. So the cleaning of surface before thermal spraying has great importance

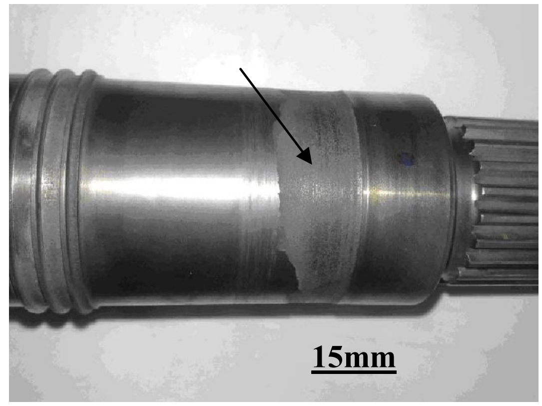

Fig.7: The studied shaft after field test

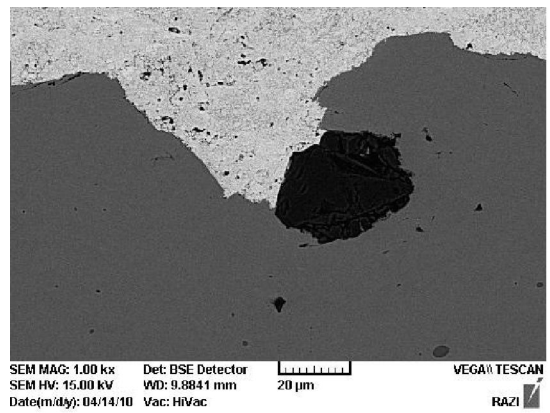

Fig.8: SEM micrograph a sand particle at the interface

4. Conclusion

Mechanical property of coated high speed shafts using high velocity oxy fuel thermally spraying process has been investigated. Metallurgical and mechanical investigations were employed for this purpose. A summery of conclusions is as follow:

- The residual stress in coating with 0.35 mm thickness is estimated to be -164 MPa by curvature method and 148±30 MPa by hole drilling method.
- Compressive residual stresses improve the fatigue behavior coated parts but preparation process could affect the fatigue life of these parts in their service.
- High velocity oxy fuel thermal spraying is an excellent choice for renewing the worn high speed turbine and compressor shafts because of good adhesion and cohesion strength as well as compressive residual stress in these coatings

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