第15卷 第2,3期
2005年9月

广东有色金属学报
JOURNAL OF GUANGDONG NON-FERROUS METALS

Vol.15, No.2,3
Sep 2005

Article ID: 1003-7837(2005)02,03-0476-06

Influence of HVOF coating on the HCF of 300M low alloy steel

DENG Chun-ming(邓春明)[1,2], LIU Min(刘 敏)[1], ZHOU Ke-song(周克崧)[1], SONG Jin-bing(宋进兵)[1], WU Chao-qun(伍超群)[1,2], KUANG Min(况 敏)[1]

(1. Guangzhou Research Institute of Nonferrous Metals, Guangzhou 510651, China; 2. Materials and Energy College in Guangdong University of Technology, Guangzhou 510640, China)

Abstract: The ultimate methods for solving the contamination of Cr^{6+} is to replace the Cr electroplating with other techniques, thermal spray provides one of the best choices among those alternative techniques. The influence of coatings upon the fatigue performance of substrate, however, should be labeled as an important factor at some high level applications. The effects of both coatings manufactured by HVOF and Cr electroplating respectively on the fatigue performance of substrate are investigated in this article. These results show that the fatigue limit strength at $P=50\%$ of thermal spray coating is 750 MPa in comparing with fatigue limit 726 MPa for substrate, and the fatigue life increase 25%-150% when comparing with fatigue life of substrate at different stress levels. The fatigue life increases in the stress scope of 750-850 MPa even the area of thermal spray coating is subtracted. Cr electroplating coating reduces the fatigue life by 70%-95% and the fatigue limit is only 600 MPa. Fracture analysis reveals that the main fracture is initiated at the subsurface, which is 0.2-0.5 mm away from substrate surface. The analysis also observes that the crack in the Cr electroplating propagates through the interface and finally into the substrate which hastens the formation of crack origin and the extension of crack in the substrate, however, the crack in the thermal spray coating deflects at the interface, spreads along the interface, as a result, the crack forming in the coatings has no negative influence on the main crack initiator and crack extension in the substrate.

Key words: HVOF; electroplating Cr; coatings; fatigue; fracture

CLC number: TG115.5   **Document code**: A

1 Introduction

Landing gear is easily worn due to its action with ground during landing and takeoff, and traditional abrasive-resistance method is the Cr electroplating technology. Cr is deposited owing to the oriented movement of $Cr_2O_7^-$ to the cathode of D.C. where electrochemical reactions take place. The technology is featured as simplicity, low cost, high hardness, good abrasion- and corrosion-resistance and is widely applied in many industries. However, Cr electroplating technique will let off carcinogenic Cr^{6+} in its life cycle. With the improvement of environmental consciousness throughout the world, more stringent emission con-

Received date: 2005-08-10

Biography: DENG Chun-ming(born in 1976), Male, Doctor.

trol of Cr^{6+} has been promulgated. EPA stipulated that the emission concentration should be within 0.1mg/m^3 in 1995 and recently the concentration limit 0.005−0.0005 mg/m^3[1] has been suggested by OSHA. The stringent emission control greatly improves the recycle of waste and disposal costs. The final solution to the contamination of Cr^{6+} is to find other alternatives to Cr electroplating technique. America and Canada then establish organizations early or late respectively, these are HCAT and CHACT. Both organizations studied the fatigue, abrasion-resistance, corrosion-resistance and other mechanical performances of HVOF sprayed WC/17Co coating in comparing with the Cr electroplating coating; the part sprayed with coating has passed the flight-test on the P-3 and F-18E/F planes . Thermal spray coatings have been applied to Boeing 737, 757 and 767, and achieved the good results[2].

Safety requirement of material should be attached to an importance for the aviation industry, and the tradegies which caused a great number of death have taken place in history[3,4]. Coatings bring the change of surface of substrate and shoulder the loading, then it is inevitable that the coatings would have influences on the fatigue of substrate. Presently the studies on the fatigue of sprayed material appear only for a few, and the results on the influence of coatings on the substrate varied or were opposite[5-8]. These results bring difficulties for the fatigue life analysis of key parts, and lead to hidden danger to aviation industry. Fortunately, the fatigue performance of sprayed material is obviously better than Cr electroplating coating[8-11]. The article centers on the effect of thermally sprayed coating on the fatigue of substrate in comparison with the Cr electroplating, and analyzes the fatigue failure mechanism and determines the influence of coating on the fatigue of substrate.

2 Experimental

2.1 Spray and specimen preparation

300M low alloy steel is commonly employed in landing gear. The material is modified from 4340 steel by adopting fine heat-treatment technique and low temperature tempering at 500K.

The hourglass specimens were machined, and were sprayed via the unique coat HVOF. Coating material is WC/17Co manufactured by agglomerated, sintered, and particle size distribution is 5-30 micron. The machined specimens were degreased with supersonic in ethanol, then grit-blasted using Alumina at compression 0.5 MPa. Finally the treated specimens were prepared for spraying. The thickness of coating is 100 micron. After polishing with diamond abrasive belt to roughness 0.2 micron, the specimens were presented to experiment the fatigue property. Cr electroplating coating is fabricated from a factory majoring in producing such a coating, both the thickness of coatings were restricted within 75μm.

2.2 Experiments and Analysis of fatigue

Fatigue method is observed to the norm HB5287-96. The polished specimens were experimented on the fatigue machine AMSLER-5100. which load at the precision of $\pm 2\%$, at room temperature axially. The stress ratio R is −1, and loading frequency is 133Hz. The infinite fatigue life is designated to be 10^7 cycles. Optical microscopy and scanning electronic microscopy (SEM) were used to analyze the fracture and its cross-section.

3 Results and discussion

3.1 Influences on fatigue of substrate

Fatigue lives of substrate, Cr electroplating coating and HVOF coating at $P=50\%$, under different stresses were presented in Table 1, where SUB, EHC and TSC denoted as substrate, Cr electroplating and thermal spray coating respectively. The table shows that the fatigue life of Cr electroplating coating is evidently lower than the substrate and HVOF coating, and at $P=50\%$ the fatigue limit is only 600 MPa by comparison with 720 MPa and 753.3 MPa for substrate and HVOF coating respectively.

Table 1 Comparison at different stress for $P=50\%$

Stress/MPa	SUB	EHC	TSC
840(720)	1380400	1137600	2848000
930(780)	440600	616600	602600
1020(840)	166000	244300	240800
Fatigue limit	726.7	600	753.3

Note: stress level in bracket for EHC

The log-log curves for three conditions material either coated or uncoated are presented in Fig. 1. Considering the effect of coatings, the fatigue limit at $P=50\%$ is modified as 717.4 MPa (5% total area) which is 1% lower than substrate and the 2% load fluctuation. The result shows that HVOF coating has no negative on the fatigue performance of substrate. However, the influences of both coatings should be obtained at different stresses, then a equation is introducedi[12]:

$$S = A \times N_f^{-m} \tag{1}$$

where S and N_f are denoted as fatigue load and fatigue life respectively, and A and m are coefficients determined by the performance of tested material and testing condition. According to the linear digression at success ratio $P=50\%$, A and m can be determined and are listed in Table 2.

Table 2 A and m for different conditions

Coefficients	SUB	EHC	TSC	TSC
A	2710	2900	2256	2351
m	0.083	0.099	0.067	0.073

The equation about decrease of fatigue life at different stress level in comparing with substrate is presented as following:

$$D = (1 - N_c/N_{sub}) \times 100 = [1 - \frac{(\sqrt[m]{S/A})_{sub}}{(\sqrt[m]{S/A})_c}] \times 100 \tag{2}$$

where c is denoted as strengthened by coatings, sub as substrate.

The decrease of fatigue life at different stress at $P=50\%$ is depicted in Fig. 2 correspondingly. The part under $y=0$ shows the increase ratio of fatigue life, conversely, the upper part decrease ratio both comparing with substrate. Fig. 2 shows that the fatigue life of Cr electroplating decreases 70% if the stress level is under 800 MPa, while the value rises to 90% if the stress is over 800 MPa. As a general, the Cr electroplating has seriously negative effect on the fatigue life of substrate. Comparatively, the fatigue life is increased by 25% after HVOF coating, and even the coating area is subtracted, there is 10% increase at the stress scope 750—850 MPa. As a whole, the coating via HVOF finds no negative effects on the fatigue life of substrate.

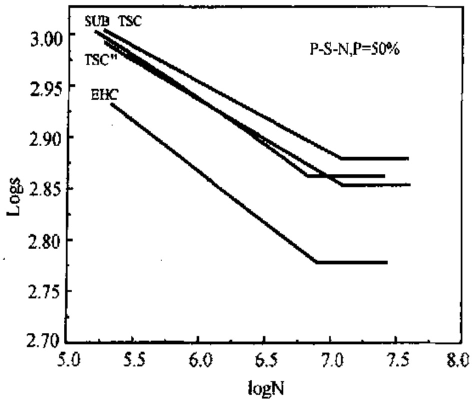

Fig. 1 Log-log curves at 50%P for 3 techniques TSC—thermal spray coatings; SUB—substrate; EHC—Cr electroplating coatings; TSC"— thermal spray coatings by subtracting 5% area

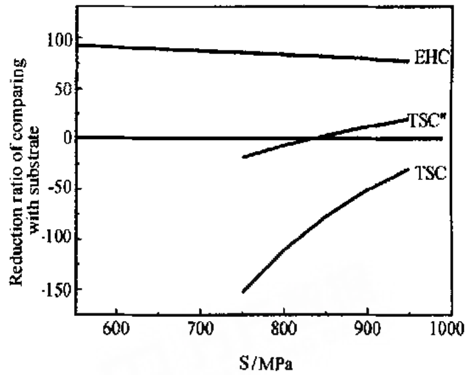

Fig. 2 Reduction ratio of fatigue life comparing with substrate at different stress level TSC—thermal spray coatings; EHC—Cr electroplating coatings; TSC"— thermal spray coatings by subtracting 5% area

3.2 Fracture analysis

Typical fractographs presented in Fig. 3 for both coated and bare substrate reveal clearly that the main fracture initiators all lie in substrate which is 0.2—0.5 mm away from the substrate surface. EDS analysis at substrate and crack initiator explicate that all crack initiators derive from inclusions composed by alumina, silica and calcium oxide in substrate.

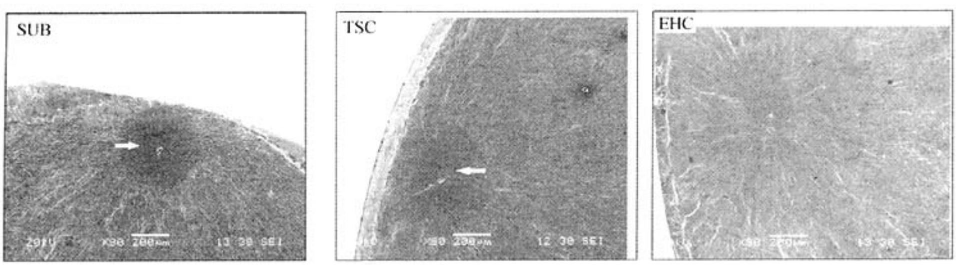

Fig. 3 Fractograph of substrate and coated 300M steels
SUB—substrate $S=740$ MPa, $N=5.99\times10^4$; TSC—thermal spray coatings $S=760$ MPa, $N=5.4\times10^6$; EHC—Cr electroplating coatings $S=620$MPa, $N=7.25\times10^6$

Fig. 4 reveals that crack takes place at the interface of thermal spray coating and forms free-standing coatings from cross-section SEM analysis, while the Cr electroplating is well bonded with substrate after fatigue test. In common, the adhesive strength of Cr electroplating coating surpasses 100 MPa and is obviously greater than the thermal spray coatings. Investigations indicated that the greater adhesive strength lower the resistance of coatings to the crack propagation through the interface or hasten to form new crack initiators on the surface of substrate. Just as presented in Fig. 4, the crack in the thermal spray coating deflects at the interface and coalesce main crack at the interface, while the crack formed in the electroplated coating extends through the interface and leads to formation of crack initiator on substrate surface.

The cracks in the thermal spray coatings have no negative effects on the formation and propagation of main crack in the substrate. Thermal spray technique produces some small damages upon the subsurface, however, the technique also leads to the compressive residual stress field due to the impact of high-speed particles upon the surface of substrate. Both actions upon the fatigue of substrate offset and we can draw a conclusion verified by the former fatigue index that thermal spray coating has no negative effects upon the fatigue life of substrate. Inversely, the crack in the Cr electroplating coating hastens the formation of crack origin and extension of main crack in the substrate, which greatly reduces the fatigue life of substrate. Besides, the tensile residual stress in the electroplated coating and micro-cracks presented in all enhance the reduction of fatigue life of substrate.

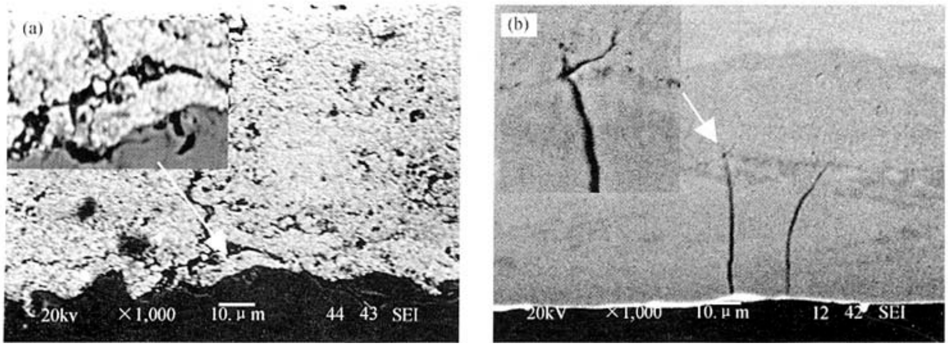

Fig. 4 SEM Cross-section of HVOF and electroplated coating and their local magnified SEMs

4 Conclusions

(1) Fatigue tests for both coated and bare substrate showed that the fatigue limit of HVOF coated 300M steel at $P=50\%$ is 750 MPa when comparing with fatigue limit 726 MPa of substrate, while the former fatigue life increase 25%—150% than the latter, even the area of coating is considered, there is moderate increase at the stress scope 750—850 MPa. The Cr electroplating coating greatly decreases the fatigue life of substrate by 70%—95%, and the fatigue limit lowers to 600 MPa.

(2) Fractograph and cross-section SEM reveal that the main crack origins are all inclusions composed by Alumina, silica and Calciun oxide which is 0.2—0.5 mm away from the substrate surface.

(3) Cracks in Cr electroplating coating propagates through the interface and finally into the substrate which hasten the formation of crack initiator and the extension of crack, however, the crack in the thermal spray coating deflects at the interface, spreads through the interface and finally the crack forming in the coatings has no negative influence on the main crack initiator and crack propagation in the substrate.

References

[1] Satrwell B D, Natishan P M, Singer L, *et al*. Replacement of chromium Electroplating Using HVOF Thermal spray Coatings[EB/OL]. www.hcat.org/documents/AESF%20Plating%20Forum%20Mar1998.

[2] Keith Legg. HVOF in Repair and Overhaul-Higher reliability at lower cost? Aviation Gas Turbine Engine O&R, http://www.rowantechnology.com/Documents/hvof/.

[3] Fatigue of material. http://www.autoworld.com.cn/mantan/yiban/yiban2.htm(in Chinese).

[4] Highly structural fatigue analysis. http://www.ansys.com.cn/cae/download/Fe-safePISheet.pdf(in Chinese)

[5] Puchi E S Cabrera, Berrios-Ortiz J A, Da-Silva J, *et al*. Fatigue behavior of a 4140 steel coated with a Colmonoy 88 alloy applied by HVOF[J]. Surface and coatings technology, 2003, (172): 128—138.

[6] Steffens H D, Wilden J, Nassenstein, *et al*. Influence of HVOF sprayed WC/Co coatings on the high cycle fa-

tigue strength of mild steel[A]. Proc 8th National Thermal Spray Conf. [C]. Houston: 1995, 469—474.

[7] Tipton A A. The effect of HVOF Sprayed Coatings on the Elevated Temperature High Cycle Fatigue Behaviour of a Martensitic Stainless Steel[A]. Proceedings of the 8th National Spray Conference[C]. Houston: 1995, 475—480.

[8] Marcelino P, Renato C Souza, Ivancy M Miguel, *et al*. Effect of WC thermal spray coating by HP/HVOF and hard chromium electroplating on AISI4340 high strength steel[J]. Surface and coating technology, 2001, (138): 113—124.

[9] Padilla K, Velasquez A., Berrios J A, *et al*. Fatigue behavior of a 4140 steel coated with NiMoAl deposit applied by HVOF thermal spray[J]. Surface and Coating technology, 2002, (150): 151—162.

[10] Hernández L, Oliveira F, Berríos J A, *et al*. Fatigue properties of a 4340 steel coated with a Colmonoy 88 deposit applied by high-velocity oxygen fuel[J]. Surface and coating technology, 2000, (68): 133—134.

[11] Lee D, Eybel R, Evans R. Development and implementation of HVOF WC/Co/Cr coating as alternative to electrolytic hard chrome plate in landing gear applications using natural gas as fuel[A]. Thermal spray 2003: advancing the science and applying the technology[C]. Ohio: ASM International (Materials Park), 2003, 371—376.

[12] Surrest S. Fatigue of materials[M]. Wang Zhong-guang translation. Beijing: National Defense industry publishing house(in Chinese), 1999.