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ScienceDirect
International Journal of Fatigue 29 (2007) 471–480
International Journal of Fatigue
www.elsevier.com/locate/ijfatigue

Fatigue properties of a SAE 4340 steel coated with TiCN by PAPVD

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Received 17 February 2006; received in revised form 22 March 2006; accepted 6 May 2006
Available online 3 July 2006

Abstract

An investigation has been carried out in order to study the fatigue performance, both in air and in a 3 wt.% NaCl solution, of a quenched and tempered (Q&T) SAE 4340 steel substrate coated with a TiCN film of ~4 μm in thickness deposited by plasma assisted physical vapor deposition (PAPVD). The results obtained show that the presence of the coating provides a significant increase, in the range of ~140–180%, in fatigue life, in comparison with the uncoated substrate, when the material is tested in air under rotating bending conditions at maximum alternating stresses in the range of ~550–700 MPa. It is also shown that when the material is tested in the NaCl solution only a marginal increase (25% at the most) in the number of cycles to failure is observed, particularly at maximum alternating stresses above ~570 MPa, which suggests that the TiCN film is susceptible to the corrosive effect of the solution under the combined action of cyclic loading. The increase in the number of cycles to failure in air is explained in terms of the high mechanical strength of the film, its compressive residual stress state and excellent adhesion to the steel substrate. It is shown that fatigue cracks nucleate at the surface of the coating and propagate normal to the substrate–coating interface without bifurcation along the latter, after going through the entire coating thickness. Under the assumption of the validity of a simple linear law of mixtures, the tensile strength of the film is estimated in ~34 GPa, very close to its absolute hardness of ~33 GPa, whereas its fatigue limit is found to be in the range of ~12.6 GPa.

Keywords: Q&T 4340 steel substrate; TiCN coating; PAPVD; Fatigue; Corrosion-fatigue; Absolute hardness; Film strength

1. Introduction

SAE 4340 steel constitutes a very important engineering material employed in the manufacture of many different parts and components which encompass automotive crankshafts and rear axle shafts, aircraft crankshafts, connecting rods, propeller hubs, gears, drive shafts, landing gear parts and heavy duty parts of rock drills, among others. All these parts involved in many different applications could be subjected to combined severe conditions of wear, corrosion and cyclic loading and therefore, hard coatings could be employed for improving the surface properties of such components. However, the improvement of surface properties by means of coatings in order to increase the performance against wear and corrosion could deteriorate significantly the fatigue properties of the substrate. Typical examples of this situation are the deposition of electrolytic hard chromium (EHC) on high strength steel parts and to a lesser degree the use of electroless NiP (EN) and thermal spray coatings [1–11].

In this context, in a recent investigation, Nascimento et al. [8] carried out a study in order to analyze the effects of a tungsten carbide coating applied by HVOF thermal spray and of EHC deposited by conventional and high

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0142-1123/$ - see front matter
doi:10.1016/j.ijfatigue.2006.05.003

efficiency fluoride-free processes, on the fatigue, corrosion and abrasive wear behavior of an AISI 4340 high strength steel. Their results showed that the coatings deposited gave rise to an impairment of the fatigue properties of the high strength steel substrate under rotating bending conditions and that the tungsten carbide thermal spray coating provided the better performance among the different coatings tested. More recently, Ortiz-Mancilla et al. [11] carried out an investigation in order to study the effect of a hard Cr deposit on the fatigue properties of a quenched and tempered (Q&T) SAE 4140 steel. The results obtained showed that both fatigue life and fatigue limit were substantially reduced in comparison with the uncoated material. SEM observations carried out on cross-sections of the fractured samples showed that the fatigue fracture of the coated specimens initiated at the substrate-deposit interface and that the coating remained well adhered to the substrate during fatigue testing. The fracture surfaces of the specimens tested showed multiple crack initiation sites, which led to the conclusion that the coating acted as a crack source for the steel substrate.

Regarding the use of hard coatings deposited either by PVD or CVD onto structural steels, the results reported in the literature indicate a different trend to that of the EHC, EN and thermal spray coatings. For instance, Jaeger et al. [12] studied the fatigue behavior of PACVD-hard coating steel compounds. Different plasma heat treatments (plasma nitriding and carbonitriding) and hard coatings within the system Ti–Al–C–N were applied onto a high-speed tool steel S6-5-2 substrate. In the first step, the influence of nitriding and carbonitriding as substrate pretreatment on the fatigue properties was characterized. Secondly, with given optimized pretreatment conditions, the fatigue behavior of the hard coatings, TiC_xN_{1-x} and $Ti_{1-x}Al_xN$, were investigated in dependence on the stoichiometric coefficient x. Besides fatigue loading, the film compounds were comprehensively characterized with respect to hardness, film thickness, morphology of grain structure, residual stresses and Young's modulus. The results of this investigation allowed the conclusion that the TiC_xN_{1-x} films caused an increase of the fatigue fracture stress with increasing stoichiometric coefficient x. Compared with untreated steel there was a reduction of the fracture stress of 12% for $x = 0$ and a improvement of 17% for $x = 0.53$. Also, it was concluded that with the $Ti_{1-x}Al_xN$ films, the fatigue fracture stress decreased with increasing the stochiometric coefficient x. Compared with untreated steel there was an improvement of the fracture stress of 11% for $x = 0$ and a reduction of 9% for $x = 0.75$. According to the results, the changes in fatigue strength correlated well with the course of the compressive residual stresses of the films. Optimal hard coating yielded an improvement of the fracture stress in bending fatigue of approximately 17% as compared with untreated steel, however, there was no improvement compared with an optimum plasma nitrided steel without hard coating.

More recently, Baragetti et al. [13] conducted an investigation in order to study the fatigue resistance of a CrN coating deposited by PVD onto a 2205 duplex stainless steel substrate, by means of four-point bending tests. The effect of substrate preparation (rolling, polishing and shot peening plus polishing) was also evaluated in terms of both surface residual stress data and fatigue behavior. The results of the mechanical tests were interpreted by means of microstructural analysis and surface residual stress distribution. The experimental fatigue tests carried out revealed an enhancement in the fatigue life of the coated specimens. Also, according to the authors, the most important parameter influencing the enhancement of the fatigue resistance of coated specimens was the compressive surface residual stress field induced by PVD coatings (with surface residual stresses higher than 1 GPa). It was also reported that for applied stresses that would cause the rupture of uncoated specimens, such high values of surface residual stress, even in the presence of surface defects in the coating, like large droplets, prevented any surface microcrack from propagating.

All these results are in agreement with those reported by Berríos-Ortiz et al. [14,15] and Puchi-Cabrera et al. [16], regarding the deposition of different TiN_x and ZrN_y understoichiometric films onto AISI 316L stainless steel by unbalanced close field magnetron sputtering (UCFMS) and TiN onto the same substrate deposited by plasma assisted PVD (PAPVD), respectively. These researches showed that in every case a substantial increase in fatigue life both in air and in a NaCl solution was obtained due to the deposition of the films, in comparison with the uncoated substrate.

Therefore, taking into consideration that the evaluation of the fatigue and corrosion-fatigue properties of a coated substrate constitutes an issue of utmost importance regarding the integral assessment of the performance of any coated system, the present investigation has been carried out in order to study the effect of a TiCN film deposited by PAPVD, on the fatigue performance both in air and in a NaCl solution, of a SAE Q&T 4340 steel substrate and compare the behavior of the coated material with that of the uncoated substrate. This coating was selected to carry out the present study due to its importance in the coating tool industry, where high wear-resistant materials with low friction coefficients are required.

2. Experimental techniques

2.1. Sample preparation

The present investigation has been carried out with samples of a Q&T SAE 4340 steel substrate with the following composition (wt.%): 0.34 C, 0.3 Si, 0.50 Mn, 1.50 Cr, 0.20 Mo, 1.5 Ni and Fe bal. This material was provided as bars of approximately 12.7 mm in diameter and 6 m in length, from which 10 tensile and 140 fatigue samples were machined according to the ASTM A 370 and ASTM 606