Materials and Design 33 (2012) 444–450

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Fatigue life evaluation of 42CrMo4 nitrided steel by local approach: Equivalent strain-life-time

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A R T I C L E I N F O

Article history:
Received 17 September 2010
Accepted 23 April 2011
Available online 30 April 2011

Keywords:
Surface treatments
Fatigue
Value analysis
Fatigue life
Ion-nitriding
Residual stress
Work-hardening
Mechanical characteristics
Local approach

A B S T R A C T

In this paper, the fatigue resistance of 42CrMo4 steel in his untreated and nitrided state was evaluated, using both experimental and numerical approaches. The experimental assessment was conducted using three points fatigue flexion tests on notched specimens at $R = 0.1$. Microstructure analysis, micro-Vickers hardness test, and scanning electron microscope observation were carried out for evaluating experiments. In results, the fatigue cracks of nitrided specimens were initiated at the surface. The fatigue life of nitrided specimens was prolonged compared to that of the untreated. The numerical method used in this study to predict the nucleation fatigue life was developed on the basis of a local approach, which took into account the applied stresses and stabilized residual stresses during the cyclic loading and the low cyclic fatigue characteristics. The propagation fatigue life was calculated using fracture mechanics concepts. It was found that the numerical results were well correlated with the experimental ones.

1. Introduction

The machine components working under cyclic loads are severely subjected to the threat of fatigue failure [1–4]. To cure this problem and improve the fatigue life some thermo-chemical and/or mechanical surface treatments are usually employed [5,6]. In particular, ion nitriding is being used to develop fatigue and wear characteristics of steels [7,8]. The fatigue life improvement of steels by nitriding depends on the characteristics of the nitrided layers, in particular the residual stresses distributions and the work-hardening [9–11].

It is well established that the fatigue life, in particular the fatigue crack nucleation, depends on the cumulated deformation rate in the starting potential site [12–15], independently of the stresses conditions (uniaxial or multiaxial). Consequently, many laws relating the elastic strain amplitude (law of Basquin) and the plastic one (law of Manson–coffin) to the fatigue life were established in experiments with the identification of the associated material characteristics [16–19]. Many modifications were provided to these relations, (low of MORROW) to integrate other effects to the influence factor, in particular hardening and residual stresses distributions. These relations are extended to the multiaxial and were applied successfully to consider the nucleation life-time in the case of the complex stresses [20–22]. These relations are useful for the nucleation life-time computation and require a coupling with an approach based on the fracture mechanics concepts to predict the propagation life-time. However, the majority of these relations were primarily applied to the homogeneous industrial alloy structures [23–25]. Their exploitation for the hardened layers fatigue life prediction by thermochemical treatments (carburizing and nitriding) was not made in consequence of the properties gradients which characterize these layers.

In this investigation, an experimental study was conducted to evaluate the nitriding treatment effects on the fatigue behaviour of 42CrMo4 steel. The effect on structures mechanical properties developed after ion nitriding was investigated by using a three-points bending fatigue machine, a micro-hardness tester, and scanning electron microscopy (SEM) with X-ray diffraction. Moreover, a fatigue life predictive model for nitrided parts was developed. This model considers the local multi-axial strain-fatigue life method coupled with fracture mechanics.

2. Material and experimental procedures

The studied material is a 42CrMo4 steel, usually used in mechanical industry. Its contents of alloy elements are presented in Table 1. Its structure, in a reception state (untreated), resultant from the oil quenching after austenisation at 850 °C and tempering at 580 °C during 1 h, consists of tempered martensite. These

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doi:10.1016/j.matdes.2011.04.047

Table 1
Chemical composition of studied steel.

C	Mn	Si	S	Cr	P	Mo	Ni	Al	Cu	V	Ti	Fe
0.41	0.77	0.28	0.026	1.02	0.019	0.16	0.16	0.04	0.25	<0.01	0.03	Bal.

mechanical characteristics of the 42CrMo4 steel in the untreated state are given in Table 2. The samples from untreated specimens were nitrided. The gas mixture of 20%N_2 and 80%H_2, and the temperature of 520 °C were used in ion nitriding for 30 h.

The layers nature identification was carried out by X-rays diffraction analyses and metallographic tests under the scanning electronic microscopy (SEM). Vickers indentations were made on the surface of polished samples with loads *f* equal to 49 N along the cross surface as a function of distance along depth using a Shimadzu micro-hardness tester HMV-2000.

The residual stresses state in the nitrided layer was given at the ambient temperature by X-rays diffraction on the surface under the conditions listed in Table 3. The residual stress profiles in depth were established using the hole drilling method. The holes were drilled incrementally by a 2 mm diameter drill rotating at a high speed (2500 rpm) to avoid inducing additional residual stresses.

The role of the nitrided layers structure and their crack resistance on the endurance limit were appreciated by three-points bending fatigue tests on notched specimens (Kt = 1.6). These tests, aims a censure at 10^6 cycles, were carried out at a frequency of 15 Hertz with stress ratio $R_1 = 0.1$. The fatigue-fractured surfaces were observed by SEM. The applied stress, the crack initiation position were then analysed.

Table 3
X-ray diffraction conditions.

Target	Cr
Wavelength (Å)	2.2897
Filter	V
Current (mA)	5
Voltage (kV)	20
Goniometer tilt	Ψ
Young's modulus, E (GPa)	210
Poisson's ratio, ν	0,33
Number of Ψ angles	13 (from −36.3° to +39.2°)
Number of θ angles	2 (0° and 90°)

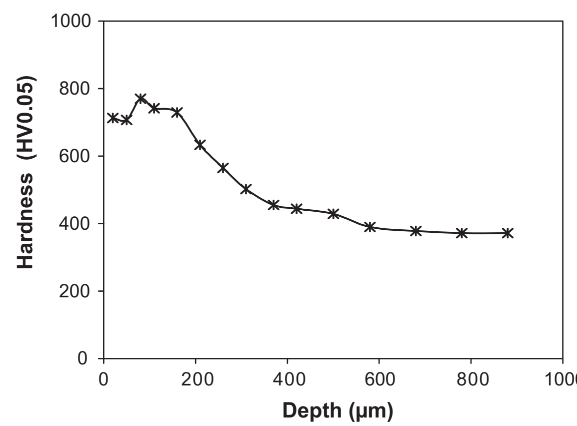

Fig. 1. Hardness profiles.

3. Results

3.1. Nitrided layers characterization

The micro-Vickers hardness profiles from edge to centre direction are shown in Fig. 1. The hardness values apart from the surface of the nitride specimen (356 HV) were similar to those of the untreated specimen. The hardness decreases from surface to core, since the concentration of metal nitrides decreases towards core. The hardness values of the compound layer were about 1050 HV but rapidly decreased in the diffusion layer.

Microstructure of surface, for 42CrMo4 steel after nitriding is shown in Fig. 2. The nitride layer is composed of the compound layer, mixes phases ε and γ', of irregular depth going from 3 to 5 µm, and diffusion layer made up of nitrogen solid solution in insertion and possibly of the fine nitride precipitates or carbo nitrides. The thickness of the diffusion layer is close to 345 µm.

These structure transformations are characterized, by the formation of nitrides and carbo-nitrides in the compound layer and the micro distortions related to nitrogen insertion in the diffusion zone are at the origin of creation of the compressive residual stresses. The level of these compressive stresses decreases from surface towards the core to reach, in under layer, approximately 0.5 mm of surface (Fig. 3). The value of the compressive residual stresses at the surface is −850 MPa.

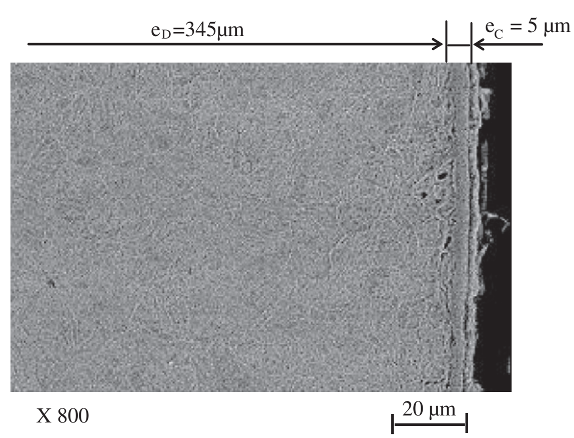

Fig. 2. Layer structure of the nitrided steel.

Table 2
Mechanical characteristics of untreated 42CrMo4 steel.

Tensile characteristics			Fatigue characteristics						Fracture characteristics		
$Rp_{0,2}$ (MPa)	R_m (MPa)	A_t (%)	K' (MPa)	n'	σ'_f	b	ε'_f	c	C (m/cycle)	m	ΔK_s (MPa m$^{1/2}$)
978	1050	16.5	907	0.089	0587	−0.05	4.72	−0.67	5.02×10^{-12}	3.38	6