Materials Science & Engineering A 672 (2016) 257–264

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Fatigue crack growth analysis of plasma nitrided AISI 4140 low-alloy steel: Part 1-constant amplitude loading

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ARTICLE INFO

Article history:
Received 5 May 2016
Received in revised form
30 June 2016
Accepted 1 July 2016
Available online 2 July 2016

Keywords:
Fatigue crack growth
Fatigue
Plasma nitriding
Constant amplitude loading

ABSTRACT

The compact tension (CT) specimens manufactured from AISI 4140 steel were plasma nitrided at 400 °C, 500 °C and 600 °C for 1 and 4 h in a gas mixture of 50% N_2 and 50% H_2. CT specimens were subjected to fatigue crack growth under constant amplitude loading in order to analyze the effect of plasma nitriding on fatigue crack growth (FCG). The crack sizes of specimens were correctly detected by a digital image monitoring system. Also, the structural and mechanical properties of specimens were characterized by XRD, SEM, optical microscopy and 3D profilometer and microhardness tester. The structural and mechanical examinations showed that the surface hardness, layer thicknesses and surface residual stresses continuously increased with increasing plasma nitriding time and temperature. It was found that plasma nitriding improved the FCG life of the material due to the formation of compressive residual stresses and nitride layers in surface and near-surface regions. Additionally, the highest FCG increase rate was obtained from 500 °C to 4 h plasma nitrided specimen with respect to untreated specimen. The formation of compound layer and braunite layer constrained the continuous increase of FCG life because of increasing embrittlement and cracking tendency of nitride layers.

1. Introduction

Numerous machine elements and structural components are subjected to fatigue while they work in service conditions. Fatigue causes premature failure of components that subjected to cyclic loading and it contributes about 90% of mechanical failures [1]. Fatigue life of a material is comprised of three periods: fatigue crack initiation, fatigue crack growth and final fracture. Also, it is very hard to accurately analyze fatigue period/properties of structural components and materials because of the complex mechanical and metallurgical nature of fatigue. In spite of this difficult analysis, the fatigue examinations have to be performed to determine the fatigue properties of engineering materials. However, there isn't a general fatigue analysis method that examines all periods of fatigue damage. For that reason, three main prediction approaches are proposed and used for fatigue analyses of engineering components: stress life, strain life and fracture mechanics approaches [1,2]. Stress life approach investigates all fatigue life of a component from the beginning of fatigue to final fracture. In stress life approach, as well known, fatigue life of a material is defined by S-N (stress-number of cycles) curves. Strain life approach generally examines the strains in critical locations (notches) and it is often used in fatigue crack initiation life estimations. In this method, ε-N curves (strain-number of cycles) are mainly used to express fatigue crack initiation phase. Additionally, fracture mechanics approach involves a specific research area that is the combination of fatigue and fracture mechanics. Fracture mechanics approach deals directly with propagation of a fatigue crack (fatigue crack growth-FCG). FCG behavior of a material is defined by a-N (crack length-number of cycles) or $da/dN-\Delta K$ (crack growth rate-stress intensity factor range) curves in this method. This method provides a prediction methodology to define fatigue propagation life of a cracked component because fatigue crack length is a physical measure of the failure [2,3].

Different surface treatment techniques, which are based on mechanical [4,5], chemical [6,7], physical [7,8] and thermochemical methods [9–11], are performed in order to improve fatigue properties of engineering components. One of the mostly used surface treatment methods is plasma nitriding. Plasma nitriding is a thermochemical diffusion process and it depends on nitrogen diffusion into the material surface in a plasma environment [12,13]. Plasma nitriding increases the surface hardness of materials and it produces compressive residual stresses on material surfaces by the formation of surface layers that contain hard

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http://dx.doi.org/10.1016/j.msea.2016.07.002
0921-5093/

nitride phases [14]. Therefore, this process is frequently used to improve fatigue properties of materials [9,10,15–17]. Effects of plasma nitriding on fatigue properties of materials were investigated in different studies by means of stress life and strain life approaches [9–11,15,18–27]. These studies commonly showed that fatigue properties of materials can be increased by plasma nitriding due to increasing surface properties. However, fatigue crack growth behavior of plasma nitrided materials approach was investigated using fracture mechanics in only a few studies that performed by one of the authors of the present study. In these studies [28–30], Şengül and Çelik investigated the influence of plasma nitriding on FCG behavior of AISI 4140 steel. They pointed out that FCG life of plasma nitrided AISI 4140 steel can be increased due to increasing surface strength. In these studies, only one plasma nitriding condition (500 °C and 2 h) was examined and effects of overload, which is one of the types of variable amplitude loading (VAL), were discussed rather than constant amplitude loading (CAL). However, as well known, plasma nitriding time and temperature directly affect the fatigue properties of materials. In the meantime, FCG behavior under CAL provide a basis for VAL predictions. For these reasons, effects of plasma nitriding on FCG properties under CAL must be determined with regard to varying process time and temperature.

Fatigue crack growth analyses, which depend on fracture mechanics approach, are performed by using CTOD (crack tip opening displacement) according to ASTM E647 standard test method [31]. In CTOD measurements, electrical potential drop and visual methods are commonly used to measure crack sizes during FCG. However, these methods have many limitations because they are affected by several factors. In electrical potential drop method, the test data are influenced by environmental variables such as temperature, air conditions etc. Also, in visual method, a fixed or traveler microscope are utilized for determination of crack size but this method can also be affected by measurement errors. Alternatively, digital image correlation (DIC)/digital image monitoring (DIM) method, which is a visual method, has been proposed to measure crack size in recent years [28–30,32,33]. DIC method has many advantages than the other methods. In DIC method, digital images are continuously recorded without any interruption and the images can be repeatedly correlated after tests. Also, DIC method is not influenced by environmental factors and measurement errors [29].

The aim of this study is to determine the effects of plasma nitriding time and temperature on fatigue crack growth properties of materials under constant amplitude loading. To achieve this aim, the specimens, which were manufactured from AISI 4140 steel, were plasma nitrided at different temperatures for times. Structural properties of the specimens were investigated by XRD, SEM and microhardness tester. For fatigue crack growth examinations, the specimens were tested under constant amplitude loading conditions by fatigue testing system coupled with digital image monitoring system. Also, fractographic investigations were performed by SEM, optical microscopy and 3D profilometer.

2. Experimental

2.1. Preparation and characterization of the specimens

AISI 4140 low alloy steel was used in this study and its chemical composition and mechanical properties are given in Tables 1 and 2, respectively. For fatigue crack growth (FCG) experiments, the compact tension (CT) specimen was selected after trial tests because it enables to stable crack growth of plasma nitrided samples. CT specimens with proper geometrical properties were manufactured in L-T direction [34] according to ASTM E647 [31]. The geometry of specimen is shown in Fig. 1. The prepared CT specimens were normalized at 850 °C and cooled down to18 °C in a furnace under argon atmosphere.

Table 1
Chemical composition of AISI 4140 steel (wt%).

C	Mn	Cr	Si	Ni	Mo	V	S	Cu	Fe
0.36	0.80	0.014	0.005	0.30	0.85	0.075	0.07	0.143	Balance

Table 2
Mechanical properties of AISI 4140 steel.

Yield stress (MPa)	Ultimate stress (MPa)	Elastic modulus (GPa)
420	650	205

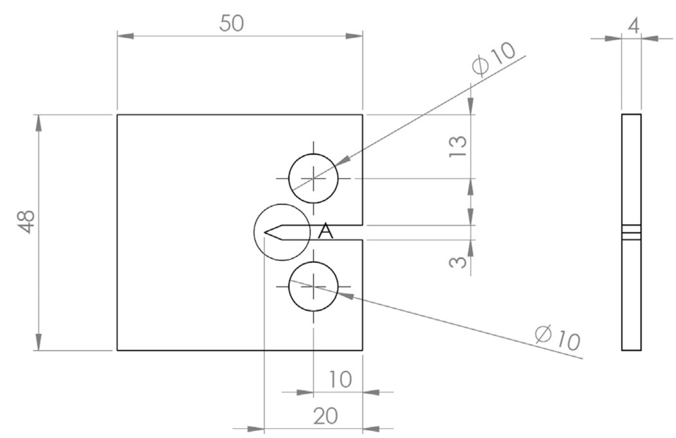

Fig. 1. Geometry of the CT specimen.

After normalization treatment, surface polishing was performed in agreement with ASTM E647 [31]. The specimens were grinded with 220–1200 mesh emery papers and then polished by alumina powder with 1 μm grain size. Thus, a surface roughness of $R_a \leq 0.2$ μm was obtained. Before the precracking and fatigue crack growth experiments, plasma nitriding treatments were performed. For this purpose, the specimens were cleaned with ethanol and then, they were placed in a plasma nitriding chamber, which was evacuated to 2.5 Pa. In order to remove any surface contaminants, hydrogen sputtering for 15 min at 500 V and a pressure of 5×10^2 Pa was applied to the specimens. Then, the specimens were plasma nitrided at 400 °C, 500 °C and 600 °C for 1 and 4 h in a gas mixture of 50% N_2 and 50% H_2 under a constant pressure of 5×10^2 Pa. Thus, all surfaces and V-notch crack starter of CT specimens were plasma nitrided.

The phase analyses were performed on a XRD-GNR-Explorer operated at 30 kV and 30 mA with CoKα radiation. The residual stresses were measured by using $\sin^2\psi$ method via XRD-GNR-Explorer. Microhardness measurements were governed by a Bruker Universal Mechanical Tester-UMT at a constant load of 100 g and a dwell time of 15 s. Also, the specimens were examined by using ESEM, FEI QUANTA-FEG 250.

2.2. Fatigue crack growth experiments

The fatigue crack growth (FCG) experiments were performed according to ASTM E647 [31]. As a standard requirement of the related standard, untreated and plasma nitrided specimens were pre-cracked until reaching a crack size of 3 mm from notch tip, which corresponds to a net crack size of a = 13 mm, in order to obtain a sharp crack starter. The pre-cracking operations were