International Journal of Fatigue 32 (2010) 584–591

Contents lists available at ScienceDirect

International Journal of Fatigue

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

# Influence of electrical discharged machining and surface defects on the fatigue strength of electrodeposited nanocrystalline Ni

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ARTICLE INFO

*Article history:*
Received 4 December 2008
Received in revised form 13 April 2009
Accepted 19 April 2009
Available online 3 May 2009

*Keywords:*
Nanocrystalline Ni
Fatigue strength
Electrical discharged machining
Surface defects
Electro-deposition

ABSTRACT

The influence of EDM and surface defects on the fatigue behavior of both conventional cold-rolled coarse grain (CG) and nanocrystalline (NC) Ni was investigated in the present work. The experimental results revealed considerable influence by EDM on the fatigue strength of NC Ni, while it has little or no effect on that for CG Ni. Specifically, EDM led to a 50–75% reduction in fatigue strength for NC Ni despite a relatively small depth of EDM affected material (∼1% of width). Rationale for this effect can be attributed to grain growth, pre-existing microcracks, and the presence of sulfur at the grain boundaries in the EDM affected zone. In addition, the pre-existing surface defects that appear to be due to impurity segregation near the electro-deposition substrate significantly reduced the fatigue resistance of ED NC Ni.

## 1. Introduction

Electrical discharge machining (EDM) is one of the most accurate abrasionless machining methods for manufacturing complex component shapes of hard and brittle materials [1–3]. EDM consists of controlled discrete electrical discharges, between a tool (electrode) and a work piece submerged in a dielectric medium. Material is removed from the workpiece by melting and vaporizing surface layers. The intense heat generated with each discharge results in severe local temperature gradients at the machined surface. On cessation of the discharge, the surface layers cool quickly and develop a residual tensile stress that can be sufficient to produce cracks in the machined surfaces [4–6]. Small surface defects induced by EDM have been known to reduce both fracture toughness and fatigue strength of certain materials [7–10], depending on the properties of the surface and near-surface regions [11].

Fatigue behavior of nanocrystalline (NC) Ni produced by pulsed electro-deposition (ED) technique [12] has been studied in depth in the past few years [13–18]. ED NC Ni has been a common choice for research on the mechanical properties of NC materials because of its FCC structure and easy attainability. In a number of studies [13,14,17,18], NC Ni has been reported to have an increased fatigue endurance limit, but a decreased resistance to crack propagation compared to conventional coarser grained Ni.

Electrodeposited NC Ni samples tested in previous studies were machined using EDM in an attempt to minimize processing induced residual stresses [14]. However, failing to properly post-treat an edge produced by EDM could possibly lead to serious degradation of the fatigue strength, even though the volume fraction of EDM affected zone is relatively small. Despite this possibility, a good understanding of how the EDM process can affect the fatigue strength of NC Ni has been lacking. Accordingly, the aim of present study was to examine the effect of EDM on the fatigue behavior NC Ni as compared with that for a conventional coarser grained Ni.

## 2. Methods

### 2.1. Materials

Sheets of 99.9% ED NC Ni with an average grain size of 30 nm and pure cold-rolled CG Ni with an average grain size of 100 μm were purchased from Integran Technologies, Inc. (Canada) and Leico Industries, Inc. (New York), respectively (compositions listed in Tables 1 and 2). Both Ni sheets had an original thickness of 0.5 mm. Fig. 1 shows the geometric shape and dimensions of the present three point-bend fatigue specimen that was based on guidelines in ASTM standard E855 [19]. Specimens were shaped using a Misubishi DWC90C Electrical Discharge Machine with a 0.25 mm diameter brass wire electrode at 80 V, 35 μm/s machining speed, and 34 ms pulse duration. Two sets of specimens were prepared using EDMunder identical conditions, one consisting of 14 NC Ni samples and another comprised of seven GC Ni specimens. Two

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doi:10.1016/j.ijfatigue.2009.04.010

**Table 1**
Chemical composition of the as-electrodeposited NC Ni (wt%).

| Co | S | Cu | C | B | P | Si | Ni |
|---|---|---|---|---|---|---|---|
| 0.071 | 0.058 | 0.023 | 0.013 | 0.0091 | 0.003 | <0.001 | Balance |

more sets of nine CG samples and 21 NC Ni specimens were fabricated using EDM with the same dimensions but then polished longitudinally on the edges using 15 μm diamond abrasive papers to a depth of at least 50 μm. The faces of all of the specimens were mechanically polished along the longitudinal direction using 15 μm diamond abrasive papers to a final thickness of 0.43 mm.

### 2.2. Fatigue tests

Experiments were performed using the three point-bend fatigue configuration, illustrated in Fig. 2, according to ASTM E855 [19] with a 30 mm span and a sinusoidal deflection waveform at 30 Hz loading frequency. A total of 51 specimens were tested. The maximum stress is located at the outer fiber of the longitudinal midpoint for each sample and is given by

$$\sigma_{\max} = \frac{3PL}{2bh^2} \tag{1}$$

where $P$ is the applied load, $L$ is span, $b$ is specimen width, and $h$ is the specimen thickness. The outer fiber stress at a given longitudinal distance from the specimen midpoint, $d$, is then

$$\sigma_d = \frac{\sigma_{\max}(L-2d)}{L}. \tag{2}$$

Mean load was controlled during testing using a custom computer based data acquisition and control system that consists of a Transducer Techniques MLP-50 load cell and a Newport Model CMA-12CCCL linear motor drive (Fig. 2). A stress ratio ($R = \sigma_{\min}/\sigma_{\max}$) of 0.2 was maintained automatically during all experiments via computer feedback control of the linear drive. The data acquisition and control software used in the present work was developed using the LabVIEW graphical programming environment. Constant cyclic displacement amplitudes were imposed using a rotating cam mechanism as illustrated schematically in Fig. 2. The maximum and minimum and mean loads as a function of cycle number were recorded along with number cycles to failure for each experiment. The number of cycles to failure was defined for the present work as the number of cycles corresponding to a drop in the mean load to half of its original value.

### 2.3. Electron microscopy

Plane-view TEM specimens were prepared by twin-jet electropolishing (Struers Tenuupol-3) with 30% nitric acid and 70% methanol at 248 K. The TEM specimens were made from EDM affected edges in order to examine the structural changes that took place in this region. Due to the limited depth of the EDM affected zone, these TEM specimens were produced using the wedge technique [20]. Samples from the EDM edge were first mechanical polished to <10 μm, and then ion milled at liquid nitrogen temperature until electron transparent. All of the TEM specimens were examined in a JEOL 2100 field emission gun transmission electron microscope operated at 200 kV with scanning capability and an Oxford EDS system. Cross sections and fracture surfaces of tested samples were also inspected using a Hitachi SU-70 field emission gun scanning electron microscope. Surface topography profiles were measured on the cross sections using ImageJ image analysis software (National Institutes of Health).

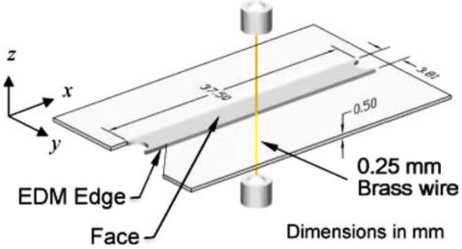

**Fig. 1.** Illustration of the specimen geometry used in the present study and the EDM process used to shape samples from NC and CG Ni sheets. All dimensions are given in millimeters.

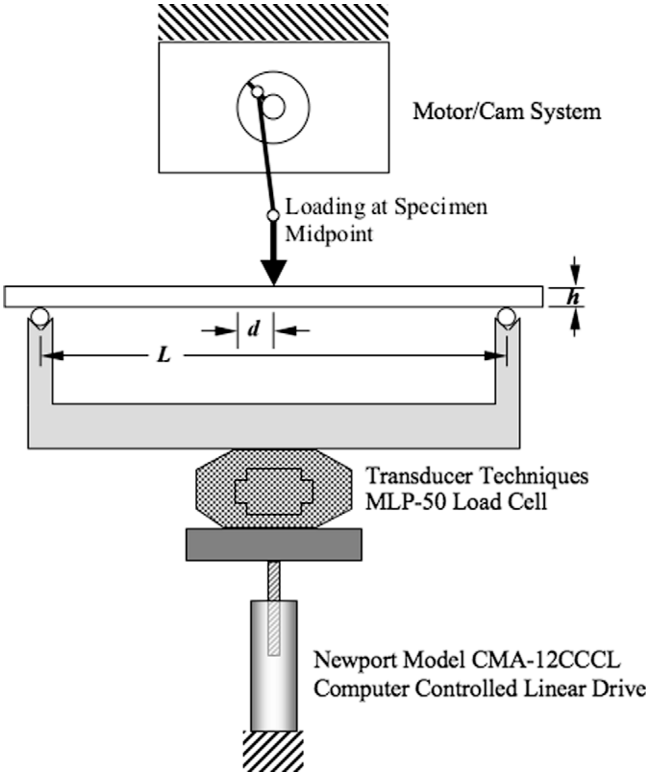

**Fig. 2.** Diagram showing the three-point bend fatigue system used in the present work.

## 3. Results and discussion

### 3.1. Electron microscopy of as-received specimens

The typical plane-view TEM images and selected area diffraction (SAD) patterns of the as-received samples are presented in Fig. 3 showing typical dislocation substructures for cold-rolled

**Table 2**
Chemical composition of the CG Ni used in the present work (wt%).

| Fe | Mn | Si | Ta | Cr | S | Al | Trace | Ni |
|---|---|---|---|---|---|---|---|---|
| 0.0013 | 0.00031 | 0.00014 | 0.0001 | 0.00009 | 0.00007 | 0.00002 | 0.00097 | Balance |