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Enhanced fatigue resistance in 316L austenitic stainless steel due to low-temperature paraequilibrium carburization

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Abstract

Fully reversed fatigue tests have been performed on wrought 316L stainless steel samples after low-temperature carburization. The resulting 25 μm case depth, with a surface hardness three times that of the core and a surface compressive stress greater than 2 GPa, leads to significantly enhanced fatigue performance. The so-called endurance limit (defined as the stress at which the fatigue life is 10^7 cycles) increased from about one-third to about one-half the yield stress (from ∼200 to ∼325 MPa). Fractographic investigations reveal that the surface stresses change the preferred site of fatigue crack nucleation from the surface for noncarburized samples to the interior for carburized samples.

Keywords: Fatigue; Austenitic steels; Carburization; Internal stresses; Tension test

1. Introduction

Fatigue cracks in steels typically nucleate at the surface. There are several reasons for this, all related to the likelihood that the highest stress amplitude will occur at the surface. For example, stress is often concentrated at grooves introduced by surface machining. Defects such as inclusions are also more detrimental on surfaces than in the sample interior. Accordingly, fatigue cracks in steels can effectively nucleate at MnS inclusions, which are common in these materials [1–3]. While MnS inclusions can be removed by dissolution, the pits they leave behind are even more detrimental [4].

Even given perfectly smooth, defect-free surfaces, stress concentrations will be higher on specimen exteriors due to shape factors. For example, Fig. 1 shows a two-dimensional finite-element analysis (FEA) of a 6.25 mm diameter stainless steel cylindrical tensile specimen. Even though the reduced cross-section is constant over a long gauge length, a stress concentration of ∼1.4 exists at the shoulders of the specimen, where it flares out into the threaded ends with a radius of 4.75 mm.

To improve the fatigue properties of steels, techniques have been developed to induce compressive stresses into the surface regions of the material, thereby reducing the stress concentrations that occur in those areas during tensile loading. Techniques such as TiN deposition [5], ion nitriding [6], laser hardening [7], shot peening [8] and case hardening [9] have all been used. In particular, nitriding [10] and carburizing [11,12] have been shown to move the fatigue crack initiation sites into the interior of steel samples.

Nitriding [6,10,13] has proven to be one of the most effective techniques for improving the fatigue life and fatigue limit of steels. It has been shown for AISI 4140 steel that ion-nitriding for 16 h gives a hardened case of 350 μm, which led to an increase of surface hardness to 715 HV_{100} from a bulk hardness of 330 HV_{100}. The ion-nitriding treatment also generated surface compressive residual stresses of 300 MPa, which led to an increase in

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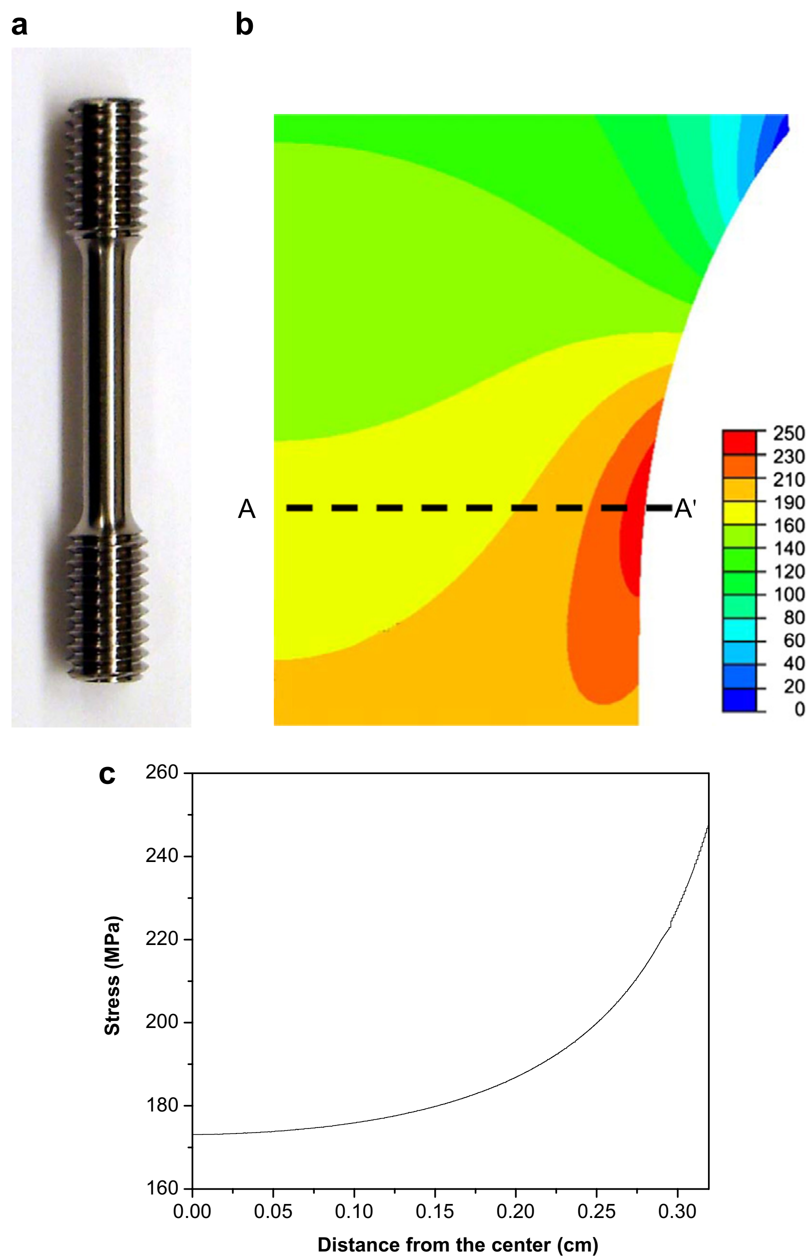

Fig. 1. (a) Photograph of a stainless steel sample; dimensions are given in Fig. 4. (b, c) FEA results for a stainless steel sample pulled in uniaxial tension at a load of 200 MPa showing (b) the principal normal stresses and (c) plot of principal normal stresses along the section A–A′.

the fatigue limit by 50%. Similar results have been shown for AISI 5140 low-alloy steel. The generation of the residual surface compressive stresses led to internal fatigue crack initiation (“fish-eye”-type crack initiation) in ion-nitrided samples, as compared to surface initiation in the case of nontreated samples. Although, the effect of ion-nitriding seems to be very beneficial for fatigue properties, ion-nitriding leads to a drastic decrease in the ductility [14,15], due to the formation of inherently brittle metal nitrides. Moreover, in the case of stainless steels, degradation of corrosion properties is associated with nitriding, due to depletion of chromium by the formation of chromium nitrides in the nitrided layer [16].

Fatigue results have been reported by Tokaji et al. [11,12] for 316 steel samples that have undergone a low-temperature (773 K) gas-carburizing process, known as the “NV Pionite” treatment. In those studies, a surface residual compressive stress of 1.5 GPa was generated, with a case depth of 40 μm and a maximum surface hardness of 940 HV, but the carburized layer formed by the NV Pionite treatment was brittle [11]. The fatigue endurance limit was increased from 300 to 390 MPa after carburization, and displayed internal crack nucleation, except for the highest stress concentrations. The internal nucleation sites were located just below the hardened cases. The fracture surfaces displayed brittle cracking through the carburized