International Journal of Fatigue 82 (2016) 350–360

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Quasi-static and cyclic failure behavior of electric sheet material

B. Bode, A. Brueckner-Foit *, F. Zeismann

Institute for Materials Engineering, University of Kassel, Moenchebergstrasse 3, D-34109 Kassel, Germany

ARTICLE INFO

Article history:
Received 12 November 2014
Received in revised form 22 April 2015
Accepted 26 April 2015
Available online 14 May 2015

Keywords:
Non-oriented electrical steel
Fatigue
Thin sheet
Fracture
Crack initiation

ABSTRACT

The failure behavior of electric sheet material is investigated under quasi-static and under fatigue loading. Specimen were cut from plates, but also from punched rotor sheets. It was found that the S–N-curve is almost a horizontal line with the maximum stress at endurance limit just below the elastic limit in a tensile test. Cyclic failure was caused by shallow notches caused by plastic deformation in the manufacturing process or by angular holes formed by debonded AlN particles. Local plastic deformation was analyzed using high resolution orientation microscopy. No slip bands were found during cyclic loading; instead, there were some kind of wide-spread deformation bands in which cyclic plasticity was localized. These findings are related to the observed failure behavior.

1. Introduction

Electric steel sheet is a functional material manufactured by modifying the magnetic properties of steel for efficient magnetism and electricity conversion. It has been used in electric motors for quite some time, but a deeper understanding of its mechanical properties is required in the context of electric mobility, as restrictions of space and weight together with more complex loading histories impose new challenges on designers. This is especially true as a typical electric car engine consists of thick stacks of very thin sheets; the typical sheet thickness well below 1 mm. Various slits and holes for accommodating the magnets, for cooling, and for stacking are punched into the stack sheets and give rise to considerable notch factors.

However, most investigations on this type of material are related to its electric and magnetic properties [1–3] whereas studies on the mechanical properties are scarce. Due to their coarse microstructure electric steel and Fe–3% Si alloys were used as a model material to study local deformation in experiments and simulation [4,5].

Very thin sheets contain only a couple of grains in thickness direction which, in turn, may pose problems with respect to mechanical characterization, as this material is not homogenous or isotropic in this direction, and individual grains and their interaction with the surrounding grains or the free surface may play a much more important role than in more substantial materials.

This study aims at identifying the damage mechanisms which may play a role in an electric motor in an automotive application. Both quasi-static loading and fatigue loading have to be taken into account, as the sheet stacks are rotating at constant frequency, if the car is moving at constant speed, and undergo load ramps during acceleration or deceleration. The material used is described in the first section together with the experimental procedure. The second section contains the results of quasi-static testing, whereas fatigue is studied in Section 4. A discussion of the damage processes observed is given in Section 5.

2. Material and specimen preparation

The material used in this study is a fully-processed non-oriented electric sheet material with 3.3 at.% Si. There are other alloying elements such as 0.73 at.% Al and 0.029 at.% N. The sheet thickness amounts to 300 μm. The surface of the sheet material was covered by a thin insulating layer which was not removed in the tests in order to preserve the original surface condition. The average grain diameter was determined to be d = 104 μm by image processing of micrographs. Fig. 1 shows a micrograph of the grain structure in depth direction. It can be seen that the grains are fairly globular and that the number of grains in thickness direction is very limited with occasional larger grains extending completely over the thickness.

The tensile tests were performed with smooth specimen (dimensions see Fig. 2a) cut from sheet material by high precision spark erosion. Some specimens were covered with a speckle pattern for deformation analysis using DIC.

* Corresponding author. Tel.: +49 561 8043680.
E-mail address: a.brueckner-foit@uni-kassel.de (A. Brueckner-Foit).

http://dx.doi.org/10.1016/j.ijfatigue.2015.04.012
0142-1123/© 2015 Elsevier Ltd. All rights reserved.

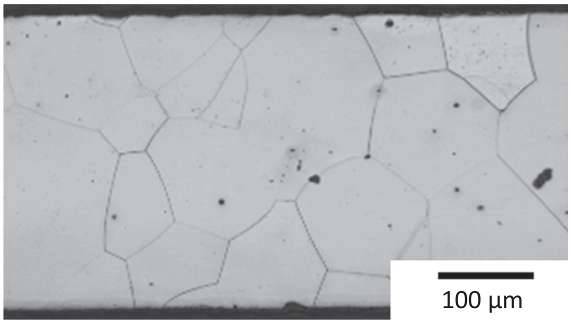

Fig. 1. Micrograph of electric steel sheet; thickness direction.

A slightly different specimen design was used for the fatigue specimens (Fig. 2b). Additionally the edges were polished (SiC paper P800 to P4000) in order to avoid local failure by edge roughness. No surface polishing was applied as these sheet materials are always used without any additional surface finishing.

However, rough edges are unavoidable in applications as components such as rotor or stator sheets are normally obtained by punching. Therefore, another fatigue specimen was designed which could be cut directly from an existing rotor sheet. Only a very small piece (see Fig. 2c) with symmetric punched edges was available due to the complex shape of the rotor sheet. Two such punch-packed pieces, which were held together by the punch, were glued into specimen holders (see Fig. 2c, adhesive DELO AD298, specimen holders are made of 90MnCrV8) which then could be mounted in the testing machine.

3. Quasi-static loading

Tensile testing resulted in a rather flat stress–strain curve with a limited amount of hardening, but quite substantial values of the fracture strain, see Fig. 3. This somewhat surprising as there was no global necking in the specimens, and the fracture surface contained large proportions of cleavage facets, as shown in Fig. 4b.

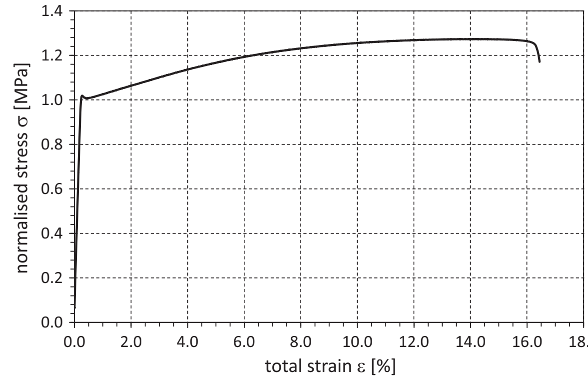

Fig. 3. Normalized stress strain curve, strain rate of $\dot{\varepsilon} = 0.00025$ 1/s.

When the local deformation was tracked using GOM/ARAMIS-system [6], it was found that plastic deformation took place at widely distributed shear bands (Fig. 5a). Final failure was triggered by the accumulation of plastic strain in one of these bands leading to crack initiation and ensuing failure by predominantly brittle facture (Fig. 5b). Even though the cleavage facets cover most of the fracture surface, there is evidence of an additional failure mechanism. It can be seen from Fig. 4a that there is a roof-like topography in the areas devoid of cleavage facets, and that the ramps are covered by slip lines indicating a large amount of plastic deformation. This phenomenon is related to ductile failure of large grains (grain diameter in the order of sheet thickness) with a failure mode similar to single crystal failure.

Hence the failure mode under quasi-static loading is in the ductile brittle transition region of this material with the unusual appearance of the ductile part being related to the fact grain size and sheet thickness are of the same order of magnitude. Independent of their final failure behavior, most grains seem to

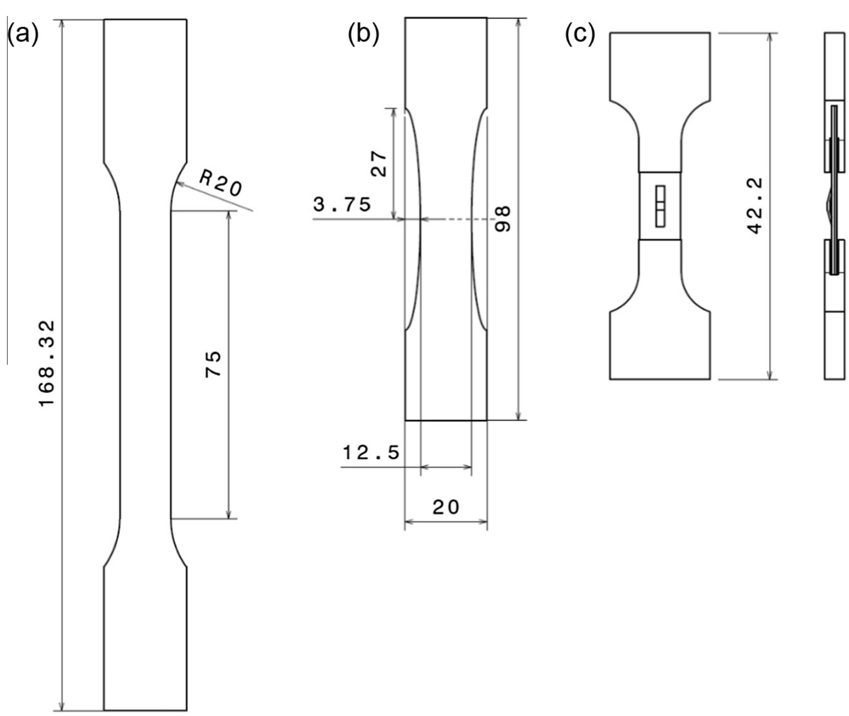

Fig. 2. Specimen geometries (scale 1:1): (a) tensile test specimen DIN 50125 H 12.5 × 50, (b) fatigue specimen, (c) special fatigue specimen, front and side view.