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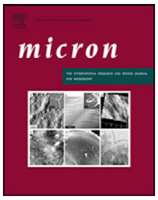

Image analysis of microscopic crack patterns applied to thermal fatigue heat-checking of high temperature tool steels

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ABSTRACT

Surface cracking or heat-checking is investigated at a microscopic scale on a hot work tool steel (X38CrMoV5) tested under thermal fatigue. Thermal fatigue tests are periodically interrupted to observe the surface of the specimens by scanning electron microscopy (SEM). A non destructive and semi-automatic method is developed to assess and evaluate the two-dimensional crack pattern initiated on the oxide scale layer formed on the specimen surface. The crack pattern is characterized by image analysis in terms of density, morphological and topological features. This technique allows to determine the number of cycles to initiate the microscopic heat-checking and to follow its evolution.

1. Introduction

One of the major damage mechanisms occurring in hot forming tool steels under thermal fatigue solicitations is the formation of a network of interconnected cracks, often named “heat-checking” (Jean et al., 1999; Medjedoub et al., 2005; Norström et al., 1981; Persson et al., 2004). This kind of crack pattern is generally observed when a surface is subjected to the removal of a diffusing heat (in cooling) or liquid (in drying), as for example in thermally quenched ceramic materials (Korneta et al., 1998), dried mud (Velde, 1999; Vogel et al., 2005), drying of thin layers and films prepared by a sol–gel process (Bockmeyer and Löbmann, 2007; Shorlin et al., 2000). Persson et al. (2004) have related the heat-checking developing on hot work tool steels to a strong thermal gradient that provides tensile stresses during the cooling phase. In brittle materials, the tensile stresses are relieved by the development of a crack pattern on the surface (Korneta et al., 1998).

Different techniques are used to analyze surface crack damage. Norström et al. (1981) evaluated and ranked the steel resistance to heat-checking by a comparative method based on in-house standard charts. This technique allows a qualitative classification of the steels, but is limitative. Indeed, such method does not give a very precise quantification of the damage grading, and it is only suitable for a specific type of damage at a given scale of observation. Moreover, this evaluation is rather subjective, since the results can vary from an observer to another. More recently, quantitative investigations have been proposed using image analysis software to evaluate the “crack density” (Andersons and Leterrier, 2005; Bockmeyer and Löbmann, 2007; Jean et al., 1999; Lemoine et al., 1986; Maillot et al., 2005; Wu and Xu, 2002). These methods constitute a more precise tool to qualify the damage rate. Different definitions (and unities) are proposed for the crack density, which are not always clearly expressed. It can be stated that the crack density is a global parameter, which solely represents the severity of the crack network, independently of its morphology. The fractal dimension, measured by the “box-counting” method, is sometimes used to quantify the complex geometry of soil cracking patterns (Velde, 1999) or heterogeneous materials under compressive loading (Yan et al., 2002). This approach, which leads also to represent the irregularity of the crack pattern by a global coefficient, generally requires different scales of observation of the same pattern, and is furthermore difficult to interpret. Some geometrical aspects, like the fragment area (Andersons and Leterrier, 2005), the crack segments length (Lemoine et al., 1986; Velde, 1999), or the orientation of the crack segments (Lemoine et al., 1986), have been in addition examined in different works.

Some studies focus specifically with topological properties (Korneta et al., 1998; Shorlin et al., 2000), and the hierarchical structure of the crack patterns (Bohn et al., 2005). These approaches, applicable to any cellular structure, provide interesting information on the structural organization of a crack network. For example, the distribution of the number of sides or neighbors of the

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Nomenclature

a	system-constant in Aboav–Weaire's law
A	area of the heat-checking cells
A_m	average area of the heat-checking cells
A_{ref}	reference area of the digital image
c_i	individual cell of the cellular mosaic
ct	cooling time of the thermal cycle
C	compactness factor
d_b	number of crack branches per unit area
d_c	number of cells per unit area
d_n	number of branching nodes per unit area
E	elongation ratio
$F_{\min}$	minimum Ferret diameter
$F_{\max}$	maximum Ferret diameter
ht	heating time of the thermal cycle
j	crack junctions class
L_c	total cracks length
$m(n)$	average number of first neighbors of n-neighbored cells
n	number of first neighbors of a heat-checking cell
$\langle n \rangle$	average number of first neighbors of the cells
nsd	variance of the number of first neighbors of the cells
N	number of cycles
N_c	number of heat-checking cells
N_b	number of crack branches
N_i	number of cycles necessary for heat-checking initiation
N_n	number of nodes
N_{sat}	number of cycles necessary to achieve ρ_{sat}
P	Crofton perimeter of the heat-checking cells
$P(A)$	frequency distribution of the area of the heat-checking cells
$P(j)$	frequency distribution of the crack junction classes
$P(n)$	frequency distribution of the number of first neighbors of the cells
$P(\beta)$	frequency distribution of angles between the radiating branches from a node
$P(\theta)$	frequency distribution of the crack branch orientations
R_a	arithmetic mean roughness
t	time
T	temperature
$T_{\min}$	minimum temperature of the thermal cycle
$T_{\max}$	maximum temperature of the thermal cycle
β	angle between the radiating branches from a crack junction
μ_2	variance of the frequency distribution $P(n)$
ρ_{hc}	heat-checking density
ρ_{sat}	saturated heat-checking density
θ	orientation of crack branches

polygonal fragments or crack junction angles can help to understand the formation mechanism of the crack network, as long as the experimental observations are carried out appropriately. Vogel et al. (2005) exploit Minkowski functions to investigate the geometry of the crack patterns formed during the desiccation of clay soils. Based on mathematical morphology tools and especially the distance function, this generic method allows to describe the morphological and topological features of any kind of crack pattern, even not fully-connected ones. But it requires that the area of the crack can be precisely evaluated, and therefore, images with a sufficiently high magnification or resolution are necessary. A complex method, based on automatic edge detection and recognition algorithms, is proposed by Lauschmann et al. (2001) to analyze the fractography of crack networks in thin layers. It consists in detecting and classifying the crack elements in finishing, crossing or passing branches in knots of the network. This method can be used to model the formation of a crack pattern in relation with fracture mechanics.

The present paper deals with a semi-automatic analysis of the superficial crack pattern from SEM micrographs, using image processing and mathematical morphology tools. This method is applied to characterize the microscopic heat-checking patterns, appearing generally on tool steels under thermal fatigue tests. The oxidation and cracking mechanisms are described. The heat-checking density is measured and some quantitative features are determined on the crack branches (length, orientation), the branching points (density, class junctions, angles) and the cells (size, shape, number of first neighbors). A complete description of the geometrical and topological features of the heat-checking pattern is reported for a unique test condition.

2. Thermal fatigue experiments

2.1. Test specimens

Thermal fatigue tests are performed on X38CrMoV5 (*AISI H11*) tool steel (see Table 1), quenched and double tempered to achieve a tempered martensitic structure with 47 HRC hardness (Jean et al., 1999; Medjedoub, 2004). Specimens are of hollow cylindrical shape with a central part of 40 mm length, a 30 mm external diameter, and an internal axial hole of 10 mm diameter, for circulation of cooling water (Fig. 1a). The specimens have a wall thickness of 10 mm in the central gauge area. The external surface is mechanically polished to reach an arithmetic mean roughness (R_a) of 0.02 μm.

2.2. Thermal fatigue rig

The thermal fatigue rig uses the induction heating of specimens by a CELES-25 kW high frequency generator (100–400 kHz). The induction frequency is about 115 kHz, resulting in a very fast heating of the specimen. During the test, continuous cooling is ensured by cold water circulating through the internal hole with a flow rate of 20 l/min. The external surface is air-cooled by natural convection. The temperature of the specimen is measured by a K-type thermocouple spot welded to the specimen surface (Fig. 1b).

2.3. Test conditions

Different thermal cycles, with a maximum temperature ($T_{\max}$) ranking from 600 to 685 °C and a heating time (ht) ranging from 1.0 to 1.6 s, are applied (Fig. 2). For all the experiments, the cooling time (ct) is adjusted to achieve a minimum temperature ($T_{\min}$) of 100 °C on the specimen surface (Table 2). In order to investigate the surface heat-checking and cracking evolution, the thermal fatigue experiments were regularly interrupted at different intervals: every 500 or 1000 cycles until 3000 cycles, then every 2000 or 2500 cycles up to 15,000 cycles, and every 10,000 cycles right up to the end of the test (Medjedoub et al., 2005).

3. Crack pattern analysis procedure

3.1. SEM image acquisition

The heat-checking surface morphology is observed using a scanning electron microscope (SEM) with a back-scattering electrons detector. A magnification of 250 times, sufficient to distinguish the micro-cracks, is selected. A cartography of a randomly selected