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# Effect of local stress on the heat-checking morphology in high temperature tool steels under thermal fatigue: Transition from multi-axiality to uniaxiality

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## ABSTRACT

Thermal fatigue experiments are performed on a high temperature tool steel X38CrMoV5 (AISI H11), under various maximum temperatures and heating rates. A microscopic interconnected crack pattern (named "heat-checking") forms on the oxidised surface of the laboratory tubular specimen. A gradual transition is observed, from a "cell-type" cracking at the centre of the specimen to a "parallel cracking" at its extremities. This variation of the morphology is well demonstrated by geometrical and topological characteristics of the crack network (micro-crack orientations, cell shape and node density), which change along the longitudinal axis of the specimen. The thermo-elasto-plastic loading of the specimen is estimated by Finite Element Calculations using ABAQUS™. Whatever the thermal fatigue conditions, a linear correlation can be established between the longitudinal and hoop stress amplitude ratio $\Delta\sigma_{zz}/\Delta\sigma_{\theta\theta}$ and the hoop and longitudinal inter-crack spacing ratio $d_{\theta\theta}/d_{zz}$. It is shown that a stress amplitude ratio close to 1 results in a multi-axial heat-checking, while a uni-axial cracking is generated when $\Delta\sigma_{zz}/\Delta\sigma_{\theta\theta}$ is close to or below 0.6. This means that the morphology of the heat-checking pattern (cell or parallel type) can be used as an indicator for the local stress ratio of the thermal fatigue specimen or industrial real tools.

## 1. Introduction

"Heat checking" is one of the main damage mechanisms that is observed on the surface of a piece of material under thermal cycling or thermal fatigue, such as in die casting and forging applications (Miquel et al., 2002; Srivastava et al., 2004; Persson et al., 2005; Le Roux et al., 2013a). Multi-directional crack patterns, forming polygonal cells, are generated on bi- and multi-layered materials (like oxide films, coating or thermo-chemical diffusion layers deposited on a ductile substrate), experiencing thermal gradients or (thermo-)mechanical loadings. This through-scale micro-cracking is generally caused by (cyclic) stresses and strains acting on the surface, due to the thermal expansion mismatch between the superficial layer and the substrate (Persson et al., 2005; Le Roux et al., 2013a; Evans and Hutchinson, 1995), and/or the difference in heat diffusivity between layers in a multi-material (Dour et al., 2008). Several studies have reported the fragmentation of brittle coatings and layers, resulting of thermally induced residual stresses during a high-temperature coating process (CVD, PVD, plasma spraying, etc.) (Evans et al., 1983; Hirsch and Mayr, 1988; Kung, 1990; Teixeira, 2001). A similar multi-directional inter-connected network is formed when a multi-axial mechanical loading is applied to the substrate (Andersons et al., 2003), such as the hexagonal crack pattern (called "island-delamination") reported in ceramic films plasma-sprayed on a ductile specimen

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## Nomenclature

| | |
|---|---|
| $a$ | system constant of Aboav–Weaire's law |
| $\langle A(n)\rangle$ | average area of a $n$-sided cell (Lewis' law) |
| $b$ | constant of the linear regression |
| $d_n$ | density of nodes (number of crack junctions per unit area) |
| $d_{zz}$, $d_{\theta\theta}$ | inter-crack spacing along the longitudinal ("$zz$") and hoop ("$\theta\theta$") axes |
| $d_{zz}/d_{\theta\theta}$ | ratio of longitudinal and circumferential inter-crack spacing |
| $D$ | distance from the centre of the specimen along the longitudinal axis |
| $E$ | Young's modulus |
| $h$ | heat-transfer coefficient |
| $ht$ | heating period of the thermal cycle |
| $j$ | crack junction class |
| $k$ | slope of the linear regression |
| $m(n)$ | average number of first neighbours of the neighbouring cells of $n$-sided cells (Aboav–Weaire's law) |
| $n$, $\langle n\rangle$ | number and average number of first neighbours of the heat-checking cells |
| $N$ | number of thermal cycles |
| $P(j)$ | frequency distribution of the crack junction classes |
| $P(\beta)$ | frequency distribution of angles between the radiating branches from a node |
| $R$ | determination coefficient of linear regression |
| $t$ | time |
| $T$ | temperature |
| $T_{\min}$, $T_{\max}$ | minimum and maximum temperature of the thermal cycle |
| $zz$ | longitudinal axis of the specimen |
| $\alpha$ | coefficient of thermal expansion |
| $\beta$ | angle between the radiating branches from a crack junction |
| $\varepsilon_{\mathrm{e}}$, $\varepsilon_{\mathrm{pl}}$ | elastic and plastic strain |
| $\varepsilon_{\mathrm{m}}$ | mechanical strain |
| $\varepsilon_{\mathrm{t}}$ | total strain |
| $\varepsilon_{\mathrm{th}}$ | thermal strain |
| $\mu_2$ | variance of the distribution of the first neighbours of the heat-checking cells (Aboav–Weaire's law) |
| $\theta\theta$ | circumferential axis of the specimen |
| $\sigma_{\min}$, $\sigma_{\max}$ | minimum and maximum stress |
| $\sigma_{zz}$, $\sigma_{\theta\theta}$ | stress in the longitudinal and the hoop direction |
| $\Delta T$ | temperature amplitude |
| $\Delta\sigma$ | stress amplitude |
| $\Delta\sigma_{zz}/\Delta\sigma_{\theta\theta}$ | ratio of longitudinal and hoop stress amplitudes |
| $\Delta\varepsilon$ | strain amplitude |
| $\Phi$, $\Phi_{\max}$ | heat-flux density and maximum heat-flux density |

submitted to equi-biaxial tensile tests (Nakasa et al., 1998). On the opposite, when a layered material is subjected to a uniaxial loading (e.g. tension or bending), a network of parallel cracks can form perpendicular to the loading direction. As an example, such cracking was observed in a ceramic coating deposited on a stainless steel sample subjected to tensile strain (Chen et al., 1999), and also in oxide films grown on metallic substrates subjected to high temperature bending (Bernard et al., 2002).

The local distribution of thermo-mechanical stresses therefore appears to be the main driving force generating either a "cell-type" cracking under a multi-axial (or at least bi-axial) loading, or a "parallel-type" cracking in the case of a uniaxial loading. In thermal fatigue, the role of the dominant local stress/strain state on the crack pattern has not been clearly demonstrated. Miquel et al. (2002) assumed that there is a link between the longitudinal/hoop stress ratio and the direction of micro-cracks and, consequently, the shape of the heat-checking cells. Indeed, as the laboratory experiments are generally conducted on finite specimens, the local stress and strain state can change near the free ends. The knowledge or direct measurement of stress and strain distribution in an oxide layer or a deposited coating is not straightforward, especially when the thickness of the layer is negligible compared to the dimension of the specimen (Bernard et al., 2002). Although models of mechanical behaviour of oxide layers exist in the literature, especially for thermal barrier coating (TBC) systems (Teixeira, 2001; Schütze, 1994; Miller, 1984; Freborg et al., 1998; He et al., 2003; Gao et al., 2003; Xie and Tong, 2005), it requires the determination of mechanical properties of the layer (e.g. density, thermal expansion coefficient, heat-conductivity, specific heat, Young's modulus, Poisson's ratio, etc. ...). In addition, the oxidation kinetics and morphological evolution of the oxide scale during thermal cycling (formation of new oxide phases, etc....) are difficult to incorporate into a thermo-mechanical behaviour model. Therefore, for the sake of simplification, the authors (Miquel et al., 2002; Le Roux et al., 2013a) have considered that the thermo-mechanical loading of the substrate material can represent the stress/strain state in the oxide layer.

In industrial forming processes, and especially in High-Pressure Die Casting (HPDC) or Hot Stamping, the tools are experiencing thermal fluctuations in service, which result in transient thermal gradients and subsequent thermal stresses and strains. Depending upon the amplitude of the solicitation, thermo-plastic or thermo-visco-plastic yielding can occur and lead to crack initiation and propagation under non-isothermal fatigue conditions. On planar surfaces subjected to multi-axial loading, an interconnected heat-checking network is generally formed, while a network of parallel cracks is observed near geometrical singularities (such as corners and holes), where a uniaxial fatigue state prevails.

The purpose of the present paper is to reproduce, under thermal fatigue (TF) laboratory experiments, these various heat-checking morphologies, by using a hollow