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Local approach contributions into the global view of the mechanical crack-tip environment formulation

Y. Katz*
co-operating with
N. Tymiak, W.W. Gerberich
Department of Chemical Engineering and Materials Science,
University of Minnesota, Minneapolis, MN 55455 U.S.A
* Corresponding author: E-mail address: katzroy@012.net.il

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Properties

ABSTRACT

Purpose: Physically based understanding, associate fracture processes to local origins. Even so, in elastic-plastic solids the continuum analysis is mainly engaged with the macroscopic scale. Beside global views the current study emphasise the coupled aspects that are determined by local and material-based factors.

Design/methodology/approach: Theoretical/experimental interfaces were adopted mainly cantered on interaction problems. Load interaction in static or dynamic loading and deformation/environment interactions were selected. For the load interaction cases, construction materials were investigated. A metastable stainless steel and hydrogen represented the environment interaction case. Experimentally, novel techniques have been utilized mainly on the nano scale including contact methodology and probe microscope visualization.

Findings: The macroscopic background that was supplemented by local findings enabled to refine viable models in quantitative terms.

Research limitations/implications: The nano mechanical approach allows additional options to be taken in terms of critical experiments or in order to improve multi-scale models.

Originality/value: The nowadays contribution by small volume activities as related to complicated technological topics are highly promising. These avenues are only in early stages, with increasing incentives to advance capabilities assisting applications in nano technology.

Keywords: Local approach; Hydrogen; Stainless steel; Contact methodology; Load interaction

1. Introduction

For the general case in which fatigue life is characterized solely by crack initiation controlled processes, both crack initiation and propagation have to be established. Thus, load interaction in fatigue is motivated by at least two objectives. First, as related to the fundamental level by taking the advantage of crack tip perturbations in order to refine the physical view of local micro mechanism associated with crack stability. Even in fatigue the intrinsic value of the monotonic fracture resistance remains an essential variable. By fracture mechanics methodology macroscopic approach is utilized realizing that the mechanical crack tip environment requires also the local input. Post overload effects have been addressed by Matsuoka and Tanaka [1], Chanani and Mays [2] and Katz et al [3]. Non linearity of significant volume at the crack tip vicinity resulted in the HRR field [4], Rice [5] and Thomson [6] suggestions that are beyond the reach of the ordinary continuum plasticity theory. The modelling of the crack tip dislocation interaction became relevant to Ductile/Brittle transition, slow crack growth and deformation/environment interaction. In the current study hydrogen and metastable austenitic stainless steel were selected emphasising the benefits in comprehensive global/local approach exploring complex interactive phenomena.

2. Materials, experiments and methodology

2.1. Load interactions

Two main alternatives were investigated. First, in monotonic loading Warm Pre Stressing (WPS) events were tracked. Fracture mechanics methodology was utilized in various elastic-plastic systems. For fundamental input, beside polycrystalline systems, single crystals were also included. Generally, the investigation followed a material approach that included high and low symmetry crystal structures, aluminium and iron based systems. In this experimental program, metastable austenitic stainless steel introduced additional complexity concerning phase stability effects. Specimen geometry varied from mini compact-disc specimen, compact tension, three point bending, tapered and single edge notched specimens, see table 1 below. Computational mechanic methodology varied from numerical finite element analysis down to modified superdislocation models, simulating the sequence of overload, unload and reload processes affecting the crack-tip field. Beside mechanical testing and response, optical and Scanning Electron Microscope (SEM) observations were added for fine scale deformation features emerging along the overload-affected zone. Finally, Acoustic Emission (AE) technique was utilized in order to explore enhanced cumulative damage mechanics associated with WPS. Additional activities as related to load interaction effect were centered on cyclic loading. Single overload may retard or even arrest cyclic subcritical crack growth depending on the overload degree. Load interactions that have been achieved by pulses or continuous viable amplitude blocks provide an extrinsic crack-tip shielding activated by an affected zone ahead of the crack-tip. Also for the fatigue investigation, a material approach was adopted as given in Table 1. Variations at the crack extension rates were monitored caused by single overloads and the crack rates vs. stress intensity profiles have been analyzed.

First, on the fundamental level, by taking advantage of the crack-tip perturbations such as changes in dislocation structures an improved physical view of the local micromechanism of the crack stability might develop. Moreover, better understanding of how irregularities in cyclic spectra affect the crack growth rate assist to improve fatigue life prediction methodology for real service conditions. Since AISI 304 metastable austenitic steel was also included in the fatigue studies, the role of phase stability aspects was introduced. For this specific system the study was conducted with load ratio R~0, frequency of 10 Hz and overloads intensification of 2.5.

2.2. Deformation/environment interaction

Metastable austenitic stainless steel systems have been selected affected by hydrogen environment. On a sound macroscopic background, nano tests were supplemented establishing as such a more comprehensive approach. All tests that followed contact mechanics methodology have been conducted at ambient temperature with a comparative study between the mechanical response with and with no hydrogen effects. Nano indentations beside continuous scratch tests were performed providing striking findings on top of the macroscopic information. This unique opportunity that is founded on global and local results opened additional dimensions for model assessments and micro mechanisms confirmation. Here to mention that previous studies in Fe 3%Si single crystals [7-10] established already that hydrogen induced subcritical crack growth in a discontinuous fashion. This discontinuous process involved sequences of crack initiation, crack arrest and reinitiation stages. The issue of crack stability affected by hydrogen in single crystals enabled theoretical engagement with deformation/hydrogen interaction models based on induced dislocations emission at the crack-tip vicinity besides shielding effects. This analysis provided also a theoretical background that facilitated the evaluation of the fine scale features findings in metastable austenitic steel systems.

Table 1.
Material approach program

Materials	Tests/Variables	Specimen geometry
Single crystals Fe-3%Si	Cyclic tension-tension With Overloads	Mini compact disc
Polycrystalline systems Al, Iron base alloys	Cyclic tension-tension or compression-compression with overloads.Various crystal structures	CT (compact tension), three point bending (TPB)
Metastable austeniticstainless steel	Cyclic tension-tension With Overloads	CT, SEN, TPB
AISI 304 metastable stainless steel	Transient activated by overloads with environmental interaction	SEN, TPB and tapered specimens
Superplastic model alloy Zn-22Al	Transient by overloads Thermal effects on fracture modes	CT specimens
Mild steel AISI 4340 steel Al-Li planar slip model material	Monotonic WPS	CT, TPB

3. Achieved results

3.1. Load interactions

Extensive research activities have been investigated in post-overload effects [1-3]. As mentioned, prior activities in iron based crystals, Chen at al [11] have revealed theoretically and experimentally the importance of the non-primary stresses regarding their domination on cyclic microcracking behavior. Superdislocation model has been developed [12] exploring shielding origins due to residuals causing transient crack growth that are affected by overload. The broad scope regarding the current issue of load interactions namely WPS, crack extension rate in fatigue as well as mild steel behavior at low temperature indicated consistent trends. Thus, confirming the importance of the mechanical environment at the process zone vicinity. Local events affect significantly the global mechanical response. Therefore, it becomes apparent that real progress depends highly on further developments in local data particularly in terms of quantitative capabilities. Note that directions here are highly important in small volume applications that require by definition local information and multiscale formulation abilities.

3.2. Deformation/environment interaction

Small volume mechanical response as affected by hydrogen is mainly compared to observations of small volume behavior with no hydrogen. Particular attention is given to the consistent length scale regarding interfacial toughness as well as the hardness at nanoscale depth values. However, with hydrogen interaction, the environment affects strongly the appropriate length scale by enhancing cleavage, intergranular process, or localized plasticity in terms of plastic instability rupture [12, 13]. While fracture modes transitions were established by fracture mechanic macrotests in terms of fracture resistance and alternating fracture mode transition Fig. 1 [14-16].

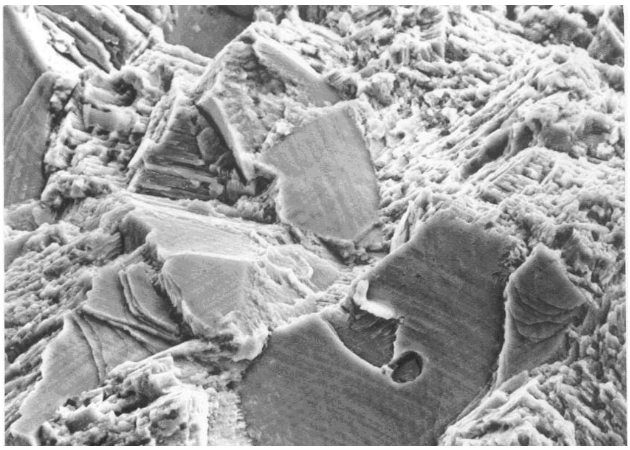

Fig. 1. SEM fractography indicating alternative modes in hydrogenated 316L stainless steel

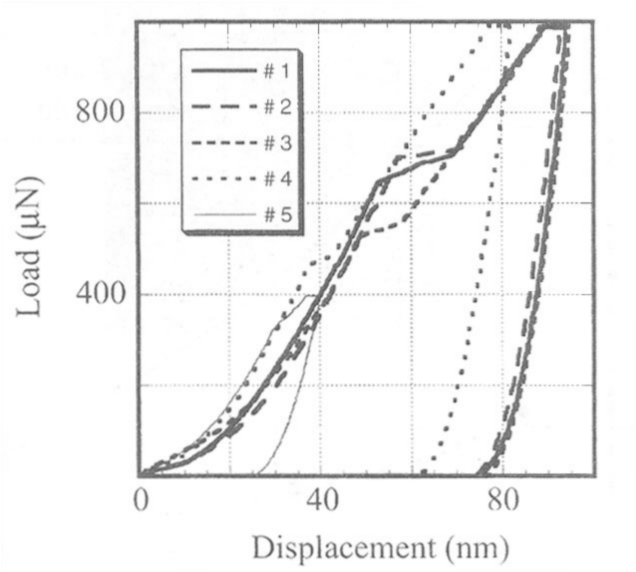

Fig. 2. Nano indentation instantly after charging at high hydrogen concentration, time increases from 1 to 5 over 35 min time frames

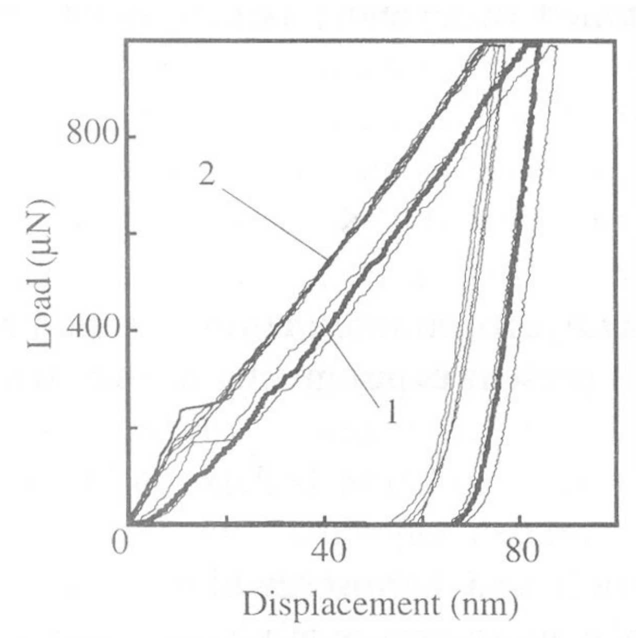

Fig. 3. Indentation into non charged samples. 1 and 2 correspond to arrays of indents in two different areas

The nano test activities [17], Fig 2 and 3 contributed a great deal to long term challenging goals. For example, in order to allow better understanding regarding the microstructure role influencing the embrittlment resistance. In addition, concerning hydrogen enhancing fracture, it appears inconsistent to have cleavage, intergranular fracture and ductile rapture occurring simultaneously as the crack growth is enhanced by hydrogen.

Assisted by nanoscale findings important insights were confirmed experimentally. Hydrogen content might affect not only the flow strength, decohesion energy or even the local stress intensity but also the slip band morphology, namely its size and character. The ramification of these findings is highly important engaging with viable proposed models. Particularly while considering multi-scale models so important to small volume technological application.

4. Conclusions

1. Post overloads effects on monotonic or cycling crack transitions are mainly dominated by non-primary stresses.
2. This underline origin remains consistent in warm pre stressing.
3. Deformation/interaction small volume experiments are beneficial for further progress.
4. Dislocation shielding at the crack is affected by hydrogen interaction.

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