Near surface secondary stresses affecting the mechanical behavior

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Abstract

Phenomenological input clearly adds to the understanding of near-surface secondary stresses (residuals) implications on the global trend of the mechanical behavior. The current study relies on critical experiments that intended to determine the role of secondary stresses on fracture and fatigue processes. Frequently, the ability to shed light on the aforementioned issues is hindered by various factors acting along the same direction. For example, phase-stability effects, strain hardening, crack-tip blunting or closure beside residual stresses introduce complexities in Fatigue Crack Propagation Rate (FCPR) perturbations under imposed-load interactions. Experimentally based cases that are related to fatigue-crack initiation and propagation, monotonic fracture toughness parameters variation due to residuals are described and evaluated. It becomes apparent that a local approach promises further insights into the significant role of near-surface stresses on the global mechanical behavior in various circumstances.

1 Introduction

In a wide span of technological applications the near surface residual stresses are of special interest. These become even more so with the notion that surfaces as such provide higher propensity for crack initiation sites and failure. Activation of the local secondary stress field might result from ample origins. Cold working, heat treatment, surface modification or coatings provide good cases. For example, in elastic/plastic metallic solids surface modification by shot peening, cavitations jet peening, laser peened surfaces and others are frequently suggested in order to prolonged fatigue life. Early studies by Mclintock [1] already pointed out the necessity to explore residual stress field
effects and for blunt notch situation this has been accomplished [2]. Nakasa et al [3] addressed residual stress effects in high strength steel due to over loads in blunt notched samples. This activity has centered on measurements as related to environmental crack onset incubation time. The local residual compressive state of stress due to over load effectively introduces at the crack tip a local macroscopic shielding. The important point here is that this shielding factor can cause a significant delayed failure time. By using the same residual stress model one can show that in semi brittles solids with typical Ductile- Brittle (D-B) transition, a prior elevated temperature overload can improve the cleavage resistance at lower temperatures [4,5]. The current study is still centered on supplementary information regarding a previously published work in fatigue of a typical FCC material [6]. The aforementioned investigation addressed the role of residuals on fatigue crack initiation in polycrystalline pure copper. Although the major objectives remains in those supplementary aspects, other activities in monotonic and cyclic load interaction for various crystal structures are also added. In addition, along similar argumentation, the case of Fe- Si single crystal with and with no environmental effect is described and evaluated. Such broad scope introduces the ongoing desire for critical experiments that might lead a better understanding. Although in service, empirical processes are already implemented in macro products down to micro electronic devices, more systematic studies are gradually developing. In general, near surface residual stress effects are complicated on different levels. This includes, processing procedures, testing methodologies and numerical simulation aspects. Questions regarding the dominant parameters and optimizations procedures are self explained but on top of it are also aspects with respect to the stress field redistribution and the range of the effective life. In terms of analysis and physically based assessments, considerable research work has been invested and elaborated. This activity illuminated significant aspects on one hand but has revealed long term goals on the other [7].

2 Experimental procedures

2.1 Polycrystalline pure copper

Commercially polycrystalline pure copper was selected with impurities level in the order of three hundred ppm. Standard mechanical properties were established by utilizing uniform specimens for uniaxial tensile tests. Fatigue tests were conducted by using three point bending specimens and uniaxial tension-compression specimens under strain controlled loading. The bending specimens were tested by electro-magnetic resonance system. For the tension-compression test for R= -1, crack onset was determined by replication technique with the assistance of SEM. However, for the other specimens, crack initiation was detected by the compliance change. In both cases the fatigue initiation life was aimed to develop a damage evolution rule for the fatigue crack initiation stage. The strain controlled tests were limited to a constant number of 10,000 cycles at 5Hz. All tests were performed at ambient temperature. For an appropriate
background, dislocation structures, surface slip upset have been established by TEM, SEM and by Atomic Force Microscopy (AFM). The second element in the experimental program included the introduction of compressive residual stresses by shot peening and temperature gradients. Residuals have been determined by X-ray diffraction technique and the local residual strain has been established by fine scale features at the surface due to the slip upset. More about the experimental procedures have been elaborated previously [6].

2.2 Warm pre-stressing in steels

Material selection included AISI 4340 and the metastable austenitic stainless AISI 304 steel. Beside standard mechanical characterization fracture toughness parameters were established at 77 and 296K. At these temperatures the AISI 4340 are below and above the D-B transition temperature. For various metallurgical state variations of the D-B transition temperatures due to micro structural effects have been established by impact tests. Besides monotonic loading, fatigue tests were conducted by using electro-hydraulic closed loop system under load amplitude controlling device. Compact pre-cracked single edge notch specimens were used with cyclic sinusoidal wave form at 77 and 296K. All tests were performed at the frequency range from 0.1 to 80 Hz for load ratio of $R = 0$. The WPS intensity varied and was performed by single overload. However, for the fatigue, the regular spectra were interrupted by a similar load interaction event.

Besides supplementary information of SEM fractography, Acoustic Emission (AE) tracking has been performed with attention to the subsequential spectra associated with the imposed WPS. For the AISI 304 metastable austenitic stainless steel that is not characterized thermally by D-B transition (down to 4K) the purpose was to emphasize the role of phase stability enhancing residuals on the mechanical behavior. The WPS can be performed by significant martensitic transformation following the reaction of $\gamma \rightarrow \varepsilon' + \alpha'$ (where $\gamma$ is the face centered austenitic phase and the $\varepsilon'$ and $\alpha'$ are the closed packed hexagonal and the body centered martensitic phases respectively). In this context a comparison was desired with a non transformed but deformed austenitic phase near the crack tip enclave.

3 Experimental results

3.1 Polycrystalline pure copper

The as received pure copper consisted of 255 MPa yield stress, 30% elongation and strain hardening coefficient of 0.11. This enabled a wide span of properties to be achieved by annealing. Typical micro structure followed and an annealing heat treatment of 723K/3h in vacuum resulted in 50-100μm grain size with a low density of annealing twins. Two relevant remarks are now in order. First, the
cyclic remote applied plastic strain amplitude results in internal modifications of the low energy dislocation structures. Only this enables the extremely high plasticity to be dissipated caused by the imposed cumulative fatigue damage. Compared to the monotonic loading, fatigue plasticity enjoys a different order of cumulative plastic values that are cyclic dependent. As confirmed by TEM observations, random dislocation density is transformed to labyrinth, loop patch, veins, walls, PSB and cell structures. The role of crystal plasticity and wall construction is illustrated in Figure 1. As indicated the wall is perpendicular to the \([h01]\). Mobile dislocations as such are on the typical \([111]\) slip plane in the \([110]\) slip direction. The zone axis from figure 1a is the \([112]\) actually parallel to the wall. Schematic description of the possible dislocation dynamic which might form a wall is given in figure 2.

![Figure 1: TEM images (a) selected diffraction pattern (b) wall formation at 5000 cycles and 10^4 plastic strain amplitude.](image)

![Figure 2: Schematic description consistent with FCC crystal plasticity.](image)
Experimentally based, the vein or the wall distance reduced with the increase of the applied strain amplitude up to an asymptotic value of about 0.5μm. The following sequential events are the formation of elongated and regular cell structure. Second, as known slip upset originates from local displacement due to dislocation/surface interaction. However, not all the dislocations are interacting due strain gradients, redundant dislocations and other forest reactions. With this notion, an "efficiency factor" is defined with direct implication on the fatigue cumulative damage evolution. The remote applied cyclic strain result in local strains that dominate the propensity for micro crack onset at the near surface site. In a remote uniaxial loading the stress tensor contains only one component of \( \sigma_{11} \) to be transformed. For orthogonal coordination systems and for a second rank tensor such transformation is given by:

\[
\sigma_{12} = \delta_{11} \delta_{12} \sigma_{11}
\]

where \( \delta_{12} \) is the resolved shear stress and \( \delta_{11} \) and \( \delta_{12} \) are the directional cosines. Clearly, plastic strain amplitude is beyond a critical resolved shear stress and a local strain as related to fatigue can be defined quantitatively. In this sense a geometrical model is adopted attributing to the cumulative slip upset at the surface, associated with the critical damage. The understanding here is that micro crack initiation at the surfaces propagate due to the continuous cycling. In this context also residuals due to surface modifications can be quantitatively be assessed via the fatigue efficiency factor. For clarification a schematic fatigue segment is depicted in figure 3. As shown the slip spacing \( s \) and the slip height \( h \) are marked and can be visualized and measured by AFM.

\[
N \cdot f \cdot \Delta \varepsilon_p = \frac{h}{s}
\]

Thus, where \( N \) the number of cycles and \( f \) the fatigue efficiency factor or,
Surface Treatment VI

\[ f = \frac{h'}{N \cdot \Delta \varepsilon_p h} \]  (3)

where \( h' \) is the cumulative slip upset height. After shot peening or residuals that are introduced by temperature gradient, the exact decrease of \( f \) became evident. Additional results have been elaborated previously [6]. For a surface modification process other influences require considerations as in the case of shot peening that beside residuals imposed surface roughness occurs with significant hardening (see figure 4). For example, after imposed residuals by heat treatment in pure copper, a reduction of \( f \) was established from 3.1\% to 1.3\% for 10,000 cycles. This is a direct confirmation of the near surface compressive residuals effects on the global mechanical behavior. An additional element in the investigation included the fatigue crack initiation life. As indicated in figure 5, a kind of Coffin Manson rule even for initiation has been substantiated but with higher sensitivity to the remote applied plastic strain amplitude. The typical exponent for initiation is approaching -1 in contrast to the frequently quoted value of -0.5 for the total fatigue life.

![Figure 5: Experimentally based \( \varepsilon_p \) as a function of \( N \) for crack initiation in pure copper.](image)

3.2 WPS in steels

Schematic illustration of WPS by single over load is shown in figure 6.
It became evident that load interaction affect monotonic loading as well as the steady state FCPR behavior. For AISI 4340 WPS results in significant increase of the fracture toughness below the D-B transition temperature. For two microstructural conditions the following results have been established. For yield stress of 350 and 680 MPa for 296 and 77 K respectively a determined ratio of 
\[
\frac{K^\text{W}}{K_{\text{IC}}} = 1.52
\]
for WPS intensity of \( \beta = 0.75 \) (\( \beta = K_{\text{app}}/K_{\text{IC}} \) where \( K_{\text{app}} \) is the applied and \( K_{\text{IC}} \) is the value at 296K). Lower value was established for an additional heat treatment condition resulting in yield stress value of 680 and 935 MPa for 296 and 77 K respectively. Here 
\[
\frac{K^\text{W}}{K_{\text{IC}}} = 1.30
\]
namely a more moderate increase of the cleavage resistance.

For the AISI 304 metastable austenitic steel the generic phenomena of FCPR retardation due to single load WPS prevailed. However, the exact recovery line-profile differed remarkably. The major change in the case of martensitic transformation has been attributed to localization. Thus, between \( \gamma \) decomposition, martensitic phase and the deformed \( \gamma \), a significant secondary compressive stress field occurred with different implications on the global behavior. This point could be formulated also quantitatively with the assistance of a mathematical model. In this context an electric capacitor discharged function was utilized as addressed by Gamache and McEvily [9] for fatigue closure. For similar conditions the effectiveness of the deformed case was less than 70% as compared to the transformed martensitic case. For the latter, the enhanced localized dilatational stresses provided higher shielding at low temperature.

4 Discussion

Practically, one can argue that the separation ability of residual stresses from other effects might have only benefit concerning basic concepts.
Table 1: Summary of a material approach activity in WPS

<table>
<thead>
<tr>
<th>Materials</th>
<th>Tests/Variables</th>
<th>Specimen Geometry</th>
<th>transient origins And mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single crystals Fe-3%Si</td>
<td>Cyclic tension-tension with overloads. Overload intensification factor</td>
<td>Mini compact-disc specimens</td>
<td>Residual-stress in a subcritical growth confined to the cleavage plane.</td>
</tr>
<tr>
<td>Polycrystalline systems Al, Iron base alloys</td>
<td>Cyclic tension-tension or tension-compression with overloads. Various crystal structures, overload intensification factor, under subsequential fatigue, constant or variable amplitude range.</td>
<td>CT (Compact Tension) and three point bending specimens.</td>
<td>Blunting, closure, residual stresses.</td>
</tr>
<tr>
<td>Metastable austenitic stainless steels</td>
<td>Cyclic tension-tension with overloads. Thermal effects. overload intensification factor.</td>
<td>CT,SEN (Single Edge Notched) and three point bending specimens.</td>
<td>Dilational stresses due to martensitic transformations.</td>
</tr>
<tr>
<td>AISI 304 metastable stainless steel</td>
<td>Transients activated by overloads, with environmental interactions.</td>
<td>SEN, three point bending, and tapered specimens.</td>
<td>Residual stresses. Deformation/corrosion effects.</td>
</tr>
<tr>
<td>Superplastic model alloy Zn—22Al</td>
<td>Transients by overloads in visco elastic-plastic model material. Thermal effects on fracture modes.</td>
<td>CT specimens.</td>
<td>Residual stresses. Time dependent crack tip shielding.</td>
</tr>
<tr>
<td>Mild steel AISI 4340 steel Al-Li planar slip model material</td>
<td>Monotonic WPS</td>
<td>CT and three point bending specimens</td>
<td>To established consistency regarding the role of crack tip field perturbation on the toughness value.</td>
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Nevertheless, the exploration of the crack tip shielding effects promises significant progress in general aspects regarding the fracture process. Part of this shielding is achieved by surface modification which results not only in microstructural changes but with variations of the local stress field distribution. In the copper fatigue case, one of the striking results is still in the critical role of residuals on the local irreversible plastic strain. Here, the role of hardening is minor. Note, that the experiment allowed optimal conditions in order to facilitate direct findings as related to residuals. Heat treatment procedures were selected in order to introduce the compressive stresses that did not exceed half the yield stress and eased the AFM measurements to be consistent and decisive. A condensed description for the WPS activities by following a material approach is given in Table 1. For the fatigue case and WPS including environmental effects a superimposed local stress field model enjoyed experimental agreement. For a Fe-3%Si single crystal case under sustained load affected by external hydrogen, considerations based on compressive residuals with a modified HRR field [10] clarified crack extension perturbations after single overload [11]. The mechanisms for retardation of fatigue crack following overloads in Al-Li alloy have been addressed by Venkateswara Rao and Ritchie [12]. There, the role of closure has been particularly emphasized with attention to the external surfaces shear. Without ignoring the stress state effects, the current study included also the specimen's thickness as an independent parameter. With the assistance of AE tracking, substantial effects of the WPS were manifested even for specimens of 50mm in thickness. The crack tip shielding in this case is clearly dominated by the near surface residuals in a cleavage mode microstructure.

5 Summary and conclusions

Experimentally based, some aspects of near surface of non primary compressive stresses have been described. For the fatigue pure copper case surface modification effects on micro crack initiation was substantiated by novel techniques. The case of load interaction affecting the low temperature properties has been attributed mainly to residuals. The meaning here is, that the major component remains in the driving force. As known the crack stability equation contains both, the driving force and the material resistance. Consequently the following is concluded:
1. Local plastic strain definition in pure polycrystalline copper under cyclic loading facilitated a quantitative engagement with surface modification effects.
2. Load interaction by warm pre stressing affects the low temperature properties and the cleavage resistance in steels.
3. A superimposed stress field model that includes the near surface residuals can assist in the understanding of the phenomenological findings.
References