

FATIGUE CRACK PROPAGATION AND CLOSURE BEHAVIOR OF A DUAL-PHASE STEEL

Leonardo Barbosa Godefroid
Federal University of Ouro Preto, Praça Tiradentes 20, 35400-000 Ouro Preto MG
leonardo@em.ufop.br

Claudinei Roberto Guimarães
Federal University of Ouro Preto, Praça Tiradentes 20, 35400-000 Ouro Preto MG
leonardo@em.ufop.br

Alex Paulo Fortes Simões da Silva
Federal University of Ouro Preto, Praça Tiradentes 20, 35400-000 Ouro Preto MG
leonardo@em.ufop.br

Abstract. A fatigue study has been made to investigate the influence of K_{max} and R load ratio on the level of crack closure in a dual-phase steel (ferrite-martensite) applied in the automotive industry. Fatigue tests were performed on CT specimens (B=3.85mm) taken at T-L orientation. All tests were carried out with a load ratio R of 0.1 , 0.3 and 0.6. Crack length and crack closure were measured by the crack mouth opening displacement method. The results reveal a significant influence of K_{max} and R load ratio on closure. Near the threshold, closure levels decrease with increasing stress intensity. At intermediate ΔK levels, closure levels increase with increasing stress intensity. At high ΔK values, the specimens experience a loss in constraint, and closure levels decrease with increasing stress intensity. This behavior is verified for R=0.1 and R=0.3. On the other hand, for R=0.6 closure levels are independent of K_{max}. From fractographic and metallographic analysis, the variation of crack closure levels was shown to be directly correlated to the mechanisms of surface roughness-induced crack closure and plasticity-induced crack closure.

Keywords*. Fatigue, crack closure, dual-phase steel.*

1. Introduction

Since its discovery by Elber (1970), fatigue crack closure has been an intensely studied parameter associated with fatigue crack propagation behavior. Closure is important because it tends to alter the relationship between the applied stress intensity factor range ($\Delta K = K_{max} - K_{min}$) and that actually experienced by the crack tip ($\Delta K_{eff} = K_{max} – K_{c\,l}$) . Under constant amplitude loading, crack closure tends to decrease the applied stress intensity, resulting in a corresponding reduction in crack growth rate. Elber contributed the phenomenon of closure to the mechanism of plasticity-induced crack closure. Suresh and Ritchie (1982) introduced the additional mechanisms of oxide-induced and surface roughness-induced crack closure, and Suresh (1983, 1985) presented the effect of crack deflection on local stress intensities and crack closure. Further details on the fatigue crack closure behavior in structural materials are also given by Anderson (1995).

During the past two decades many investigations have focused on studying the various mechanisms, the measurement methods and the factors influencing the crack closure. As a result, several mechanisms for crack closure have been established and its influences on the fatigue crack growth have been documented (Suresh and Ritchie, 1984). As to the measurement methods, many different techniques such as the crack mouth opening displacement gauge method have been established (Allison, 1988) . However, there has been a great deal of confusion and controversy about the K_{max} dependence of crack closure.

Although the primary forms of crack closure have been identified, it is difficult to predict how these mechanisms interact when present together. One way in which these interactions can be viewed is by investigating the dependence of $K_{c\,l}$ on K_{max} . Crack closure has been studied in a number of alloys, in a variety of microstructural conditions, and no general pattern has emerged (Dougherty et alli, 1997; Zhu and Shaw, 1996; Jung and Antolovich, 1996; Lee et alli, 1996; Park et alli, 1995; Kumar, 1992; McClung, 1991; Hudak and Davidson, 1988; Ramage et alli, 1987; Ritchie et alli, 1987; Shang et alli, 1987; Dutta et alli, 1984). For similar alloys, crack closure has been observed to increase, decrease or remain essentially constant with increasing K_{max} .

The objective of the present work is to investigate the influence of K_{max} and R load ratio on the level of crack closure in a dual-phase steel (ferrite-martensite) applied in the automotive industry. The three different regimes of crack propagation are characterized: the threshold behavior (ΔK_{th}), the stable behavior (Paris region), and the behavior due to loss of constraint (near the fracture).

2. Experimental procedure

The chemical composition of the industrially produced steel used for this study is shown in Tab. (1). A ferritic-martensitic dual-phase steel with chromium as an alloy element has been selected.

Table 1. Chemical composition of the steel (weight percent).

Specimen code	C	Si	Mn	P	S	Al	N	Cr
DP-Cr	0.08	0.03	1.24	0.060	0.002	0.024	0.0054	0.58

The microstructures of the dual-phase steel in the longitudinal and transverse directions are shown in Fig. 1 and 2. Using LePera etching (Van der Voort, 1984), one can see the ferrite matrix (dark) accompanied by martensite (white). It's not noticeable any major tendency for anisotropy. Results of quantitative metallography using an image analyzer are shown in Tab. (2). In both materials, ferrite grains surround the martensite islands.

Typical room temperature mechanical properties of the material in longitudinal and transverse directions are also given in Tab. (2). Note the similar behavior of the steel in both directions, without anisotropy.

Figure 1: The DP-Cr microstructure, consisting of ferrite surrounding martensite (white). Longitudinal direction.

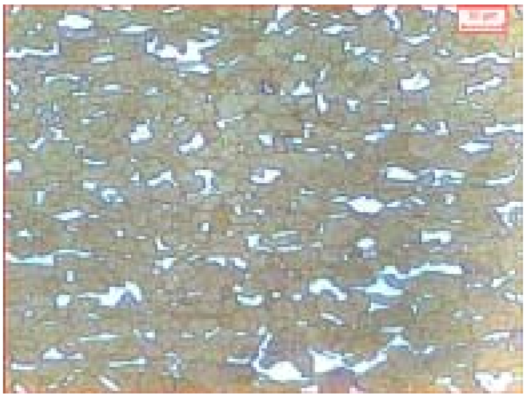

Figure 2: The DP-Cr microstructure, consisting of ferrite surrounding martensite (white). Transverse direction.

Table 2. Quantitative metallography results and mechanical properties in longitudinal (L) and transverse (T) directions of the dual-phase steel.

Specimen Code	Ferrite Grain Size (μm)	Volume Fraction Martensite (%)	Connectivity of Martensite (%)	YS (MPa)	UTS (MPa)	Total Elongation (%)	Reduction of Area (%)
DP-Cr-L	8.97	12.5	50.6	415.6	625.8	23.52	42.11
DP-Cr-T	8.42	12.4	46.3	409.0	624.8	22.75	45.83

All fatigue experiments were conducted under load control on a servo-controlled, hydraulically-actuated, closed-loop mechanical test machine interfaced to a computer for machine control and data acquisition. The fatigue crack growth curves and the closure measurements were made according to ASTM E647-99 Standard. Fracture surfaces were analysed in a JEOL scanning electron microscope. Fatigue crack path morphologies were examined on metallographic sections in an optical microscope. Crack length and crack closure were measured by the crack mouth opening displacement method.

C(T) specimens (3.85 mm thick, 50 mm wide) in T-L orientation were used for the experiments. Testing frequency was 30 Hz. The experiments were performed in ambient air (approximately 25°C, R.H. = 60%), at R-ratios of 0.1 , 0.3 and 0.6.

3. Results and discussion

Fatigue crack growth rate, da/dN, as a function of stress intensity factor range, ΔK, for the steel DP-Cr is presented in Fig. 3, for load ratio R=0.1. This figure shows the two different regions where operate the basic mechanisms of crack closure. The threshold ΔK_{th} obtained for the steel is in accordance to many Fe alloys (Liaw et alli, , 1983). Some researchers (Shang et alli, 1987; Ramage et alli, 1987; Dutta et alli, 1984; Minakawa et alli, 1982; Suzuki and McEvily, 1979) show more "dramatic" results ($\Delta K_{th} \approx 20\,\text{MPa}\sqrt{\text{m}}$), as a function of chemical composition, volume fraction and connectivity of martensite and ferrite grain size.

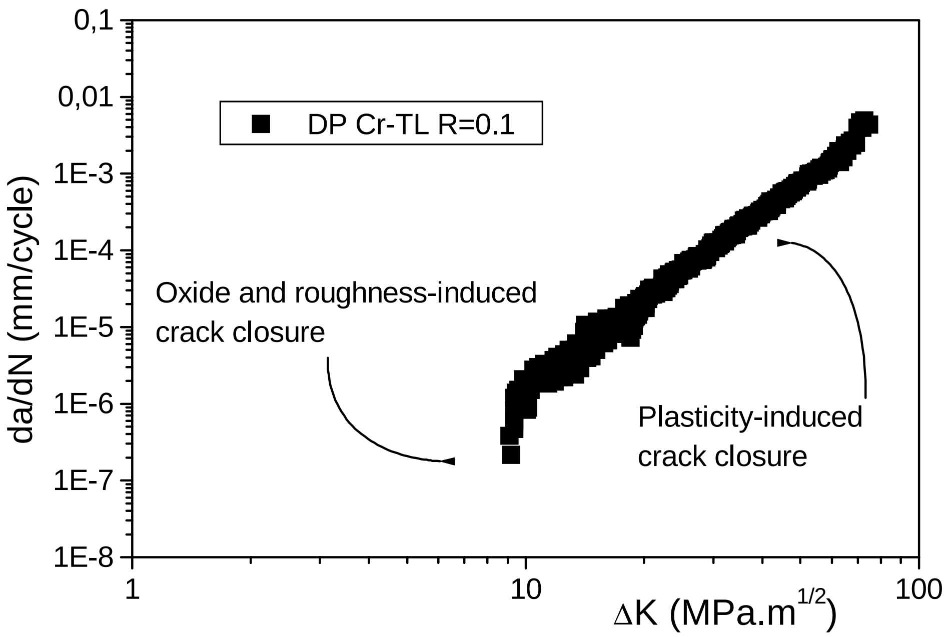

Figure 3. Variation in da/dN with ΔK for steel DP-Cr , T-L orientation, R = 0.1 .

Values of the stress intensity factor at closure, $K_{c\,l}$, were obtained as function of ΔK at R=0.1. The results are shown in Fig. 4 in the form of the ratio of closure to maximum stress intensity, $K_{c\,l}/K_{max}$, as a function of ΔK.

It is seen in Fig. 4 that the magnitude of the closure effect rapidly decreases as ΔK moves from the threshold. Such result, which shows that the degree of closure is maximum close to ΔK_{th}, is consistent with several observations for steels (Shang et alli, 1987; Ramage et alli, 1987; Dutta et alli, 1984; Minakawa et alli, 1982; Suzuki and McEvily, 1979) and other materials (Jung and Antolovich, 1996; Zhu and Shaw, 1996; Lee et alli, 1996; Park et alli, 1995; Ritchie et alli, 1987; Zaiken and Ritchie, 1985). Mechanisms that have been used to explain the high closure levels at threshold conditions include oxide-induced crack closure, roughness-induced crack closure and crack deflection.

This type of functional dependence is limited to near-threshold values of the stress intensity factor, and can not be applied in the plasticity-induced crack closure regime. Figure 4 shows that as further crack growth occurs and ΔK moves beyond the threshold regime the normalized closure levels increases with ΔK. On the one hand, Allison (1988) showed many results from the literature that indicate that $K_{c\,l}$ increases linearly with ΔK . Numerical models developed by Newman (1981, 1976) support this conclusion. On the other hand, the data of many other authors all suggest a more stable dependence (Stofanak et alli, 1983; Gan and Weertman, 1981; Vazquez et alli, 1979; Brown and Weertman, 1978; Ohta et alli, 1978; Bachmann and Munz, 1975). These variations may be due to variations in the dominant crack closure mechanism.

Another change in the $K_{c\,l}/K_{max}$ with increasing stress intensity factor well beyond the near-threshold regime (near fracture) is showed in Fig. 4. This change can be attributed to large-scale plasticity in the remaining ligament of the test specimen (McClung, 1991). In this moment constraint is completely lost, the crack becomes fully open, and crack closure disappears. The point to be made is that for behavior well beyond threshold, ΔK does not appear to be an appropriate choice for a correlating parameter to characterize crack closure.

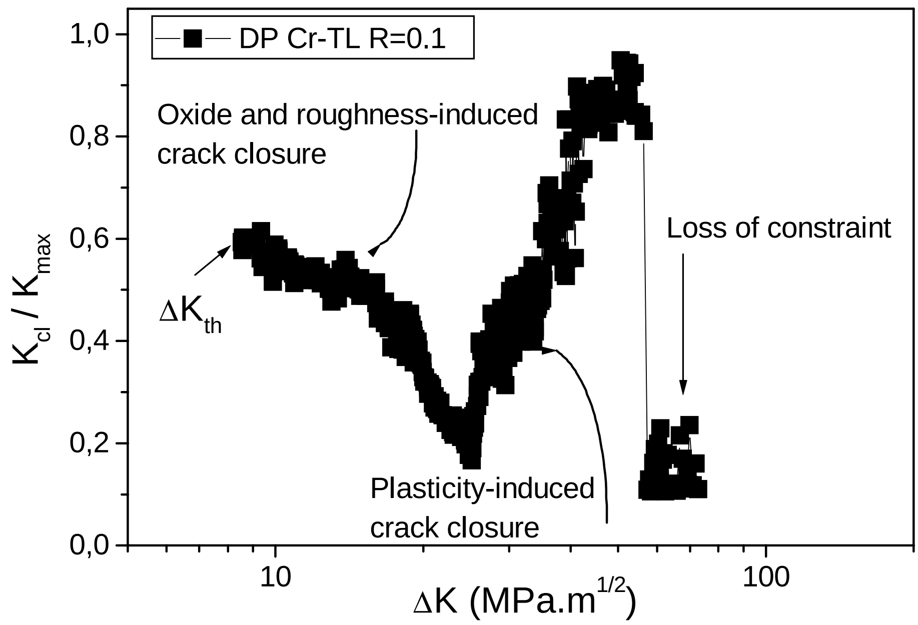

Figure 4. Experimental measurement of crack closure at R=0.1, steel DP-Cr, T-L orientation.

The effect of load ratio R on the fatigue behavior of the steel is shown in Fig. 5. An influence of load ratio is apparent with threshold ΔK_{th} values being approximately a factor of 1.7 times smaller at R=0.6 than at R=0.1. Another influence is apparent when K_{max} reaches K_{crit}. Many other authors observed the same behavior (Ritchie et alli, 1987; Zaiken and Ritchie, 1985; Dutta et alli, 1984; Stofanak et alli, 1983; Brown and Weertman, 1978; Unangst et alli, 1977).

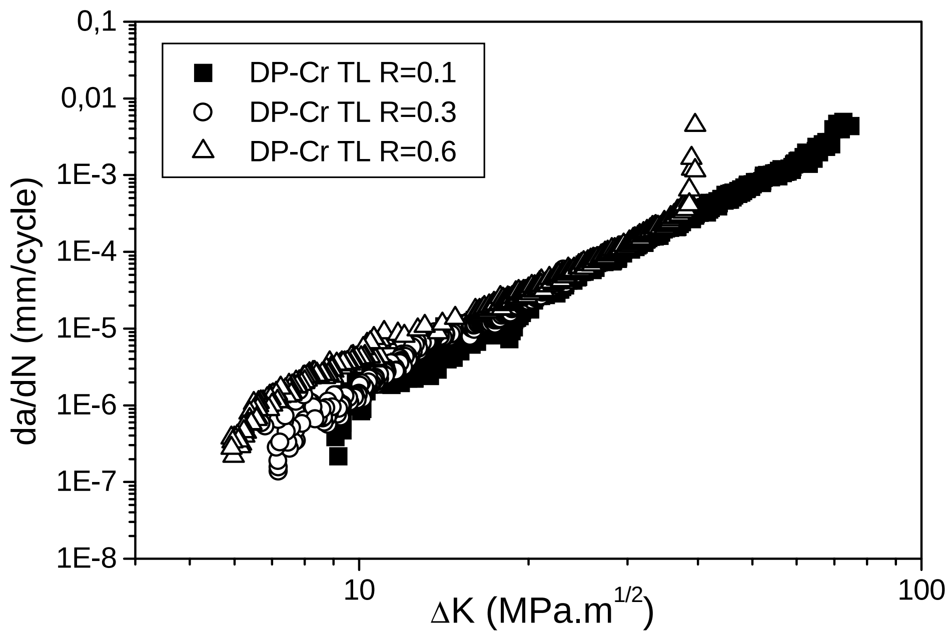

Figure 5. Variation in da/dN with ΔK for steel DP-Cr , T-L orientation, R = 0.1 , 0.3 and 0.6 .

Figure 6 shows the variation of the stress intensity factor at closure, $K_{c\,l}$, with the load ratio, R. The behavior is similar for R = 0.1 and for R = 0.3. Nevertheless, it is seen that for R=0.6 the crack closure level is essentially the same irrespective of the ΔK-value. There appears to be no fundamental dependence of fatigue crack closure level on the stress intensity factor when plasticity-induced crack closure acts alone.

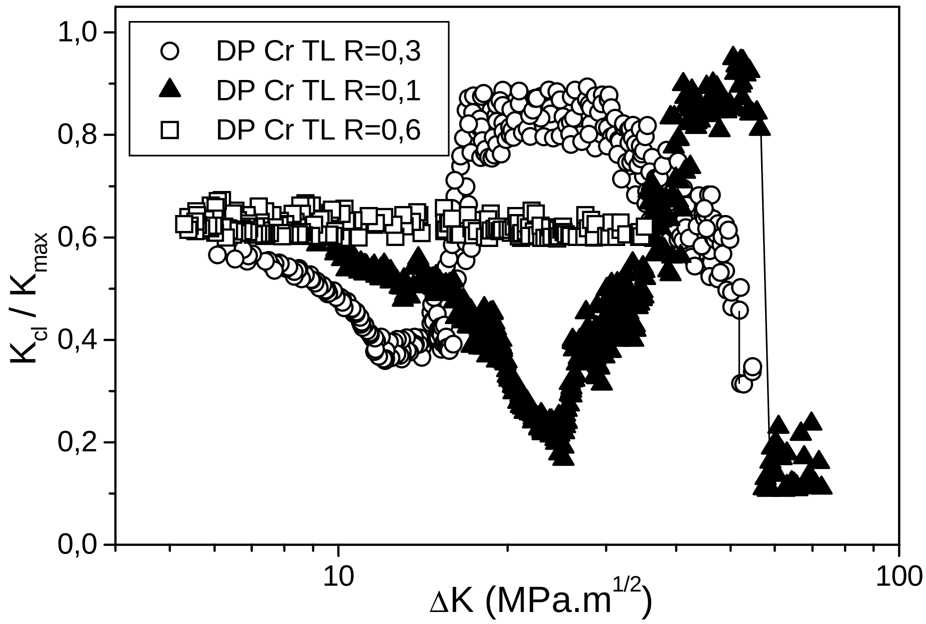

Figure 6. Experimental measurement of crack closure at R=0.1, R=0.3 and R=0.6, steel DP-Cr, T-L orientation.

Fractographic analysis of fatigue crack growth at near-threshold levels for R = 0.1 and R = 0.3 shows a predominant transgranular fracture mode, with the "hill-and-valley" type appearance and shear facets, with an associated zig-zag path primarily through the ferrite. Fig. 7 shows an example of this behavior, for R = 0.1. Such fracture shows high linear roughness and high crack deflexion angles, characteristic of extensive crack closure induced by asperity wedging (Shang et alli, 1987; Dutta et alli, 1984). At higher growth rates, fracture surfaces remain transgranular, but with some evidence of ductile cracking , and separations. This behavior is shown in Fig. 8 for R = 0.1. For R=0.6 fracture surfaces are more planar, without shear facets at near-threshold levels.

Metallographic sections were also taken perpendicular to the fracture to indicate crack path profiles. These are shown in Fig. 9 and 10 for R = 0.1. Irrespective to the ΔK level or load ratio, the crack propagates transgranulary. However, the profiles at near-threshold show evidence of more crack deflexions than at higher growth rates. Another interesting result is that the profiles at near-threshold show a crack propagation much more pronounced in the ferrite phase than in the martensite phase. Crack propagation occurred in both phases at higher growth rates.

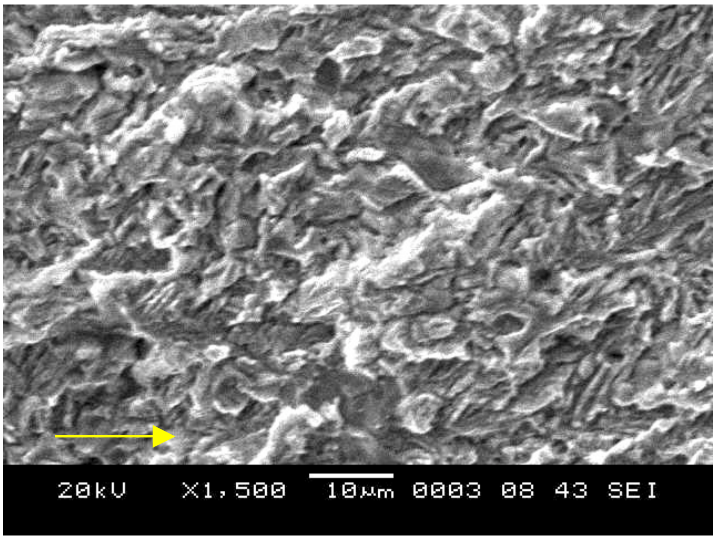

Figure 7. SEM fratography of fatigue surface close to the ΔK_{th} at R=0.1 for the steel DP-Cr T-L. Arrow indicates direction of crack growth.

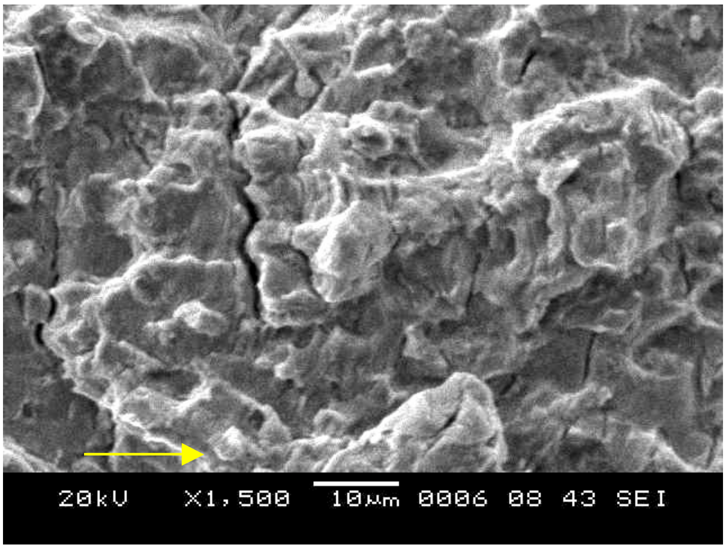

Figure 8. SEM fratography of fatigue surface at approximately da/dN = 10^{-4} mm/cycle at R=0.1 for the steel DP-Cr T-L. Arrow indicates direction of crack growth.

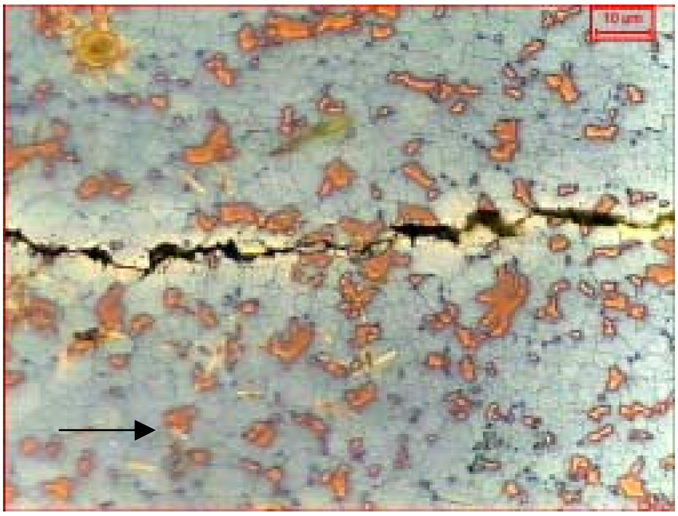

Figure 9. Le Pera etched section through the crack path close to the ΔK_{th} at R=0.1 for the steel DP-Cr T-L. Arrow indicates direction of crack growth.

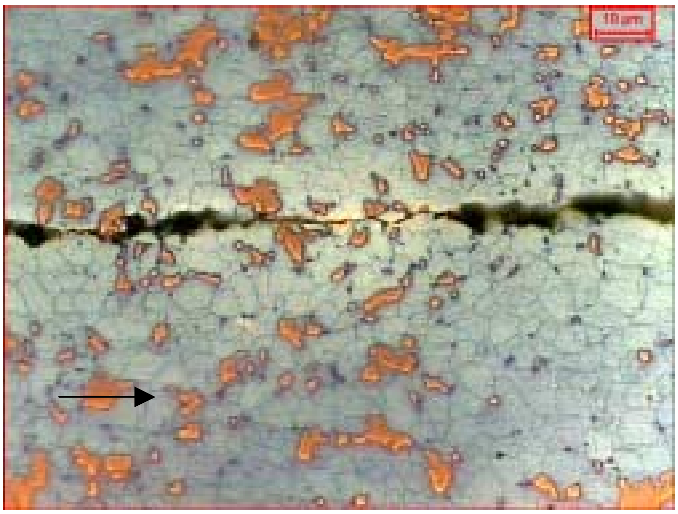

Figure 10. Le Pera etched section through the crack path at approximately da/dN = 10^{-4} mm/cycle at R=0.1 for the steel DP-Cr T-L. Arrow indicates direction of crack growth.

4. Conclusions

Near the threshold, crack closure levels increase with decreasing stress intensity factor. A variety of closure mechanisms may be operative in this region, including fracture surface roughness and crack deflection.

Outside the near-threshold region, crack closure levels increase with increasing stress intensity factor. The dominant closure mechanism in this region is residual plasticity.

When cracks are longer and applied stress intensity factor are sufficiently high, crack closure levels decrease toward zero.

Different stress ratios lead to different crack closure levels. For R = 0.1 and 0.3 the variation is similar, but for R = 0.6 crack closure levels are independent of the stress intensity factor.

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