# CORRELATION BETWEEN HYSTERESIS LOOPS AND SUBSTRUCTURE ALTERATIONS DURING FATIGUE CRACK INITIATION

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## ABSTRACT

Hysteresis loops of a low carbon steel show that cyclic softening rate and cyclic stability depend on the prestraining history ( hot and cold working) and on the level of plastic strain applied during fatigue. The hot rolled steel shows higher rates of cyclic softening which lead to longer periods of cyclic stability and therefor longer fatigue lives. The rapid rearrangement of dislocations into well defined cells during fatigue confirm that effect. A smaller range of cyclic plastic strain (and a correspondingly smaller hysteresis loop area) is not necessarily indicative of a longer crack initiation period. A positive cyclic mean stress retards the rate of substructure refining and shortens fatigue life. For nonproportional prestraining, the rate of substructure alteration during fatigue may be synergistic. However, unlike proportional prestraining crack initiation period is not prolonged. Curves of rate of variation of maximum cyclic load may be drawn which permit an estimation of both crack initiation and crack propagation periods. For the cases studied, and independent of the prestraining paths, crack initiation periods are considerably longer than the corresponding propagation periods. The shortest initiation period is about 75% of total fatigue life. The curves show that material history has a small effect on the propagation period.

## KEY WORDS

cyclic softening, dislocation cells, medium stress, maximum stress, plastic deformation range, crack initiation, crack propagation, proportional deformation, nonproportional deformation

## INTRODUCTION

The evaluation of fatigue resistance of components fabricated out of steel sheets should include, besides tests made on prototypes, the effect of the deformation history of the steel sheet. In general, fatigue life is a function of the prestraining paths (El-Sharawy *et al.*, 1993; Fredrikson *et al.*, 1988; Quesnel *et al.*, 1978). Considering the same reduction in thickness, each prestraining path imposes different levels of effective strain ($\varepsilon_e$) due to the specific state and level of stress or strain applied in each case. Consequently, the developed dislocations substructure is also characteristic (Laird *et al.*, 1989; Feltner and Laird, 1967a, b). Besides, different gradients of residual stresses may build up (El-Sharawy *et al.*, 1993 ). Therefor, for a

given range of load or strain applied during fatigue, the capacity of the steel to accommodate plastic deformation and, consequently, the fatigue life are a function of the initial characteristic dislocation structure and of the level and direction of residual stress (compressive or tensile). The effect of residual stress may be significant during high cycle fatigue since stress relief is relatively slow at these stress levels(Quesnel *et al.*, 1977). On the other hand, residual stress may be relieved after relatively few cycles during low cycle fatigue (Quesnel *et al.*, 1977, 1978). Therefore, for a given range of applied strain, the effect of residual stress may be excluded, and, for the same geometry and surface effects, fatigue crack initiation period will be a function of the initial dislocation substructure. That is, the transient period of cyclic softening or hardening, and the period of stabilization of the hysteresis loop (i.e, equilibrium between dislocation generation and annihilation) are principally a function of the substructure developed before fatigue.
Moreover, the period and type of the transient phenomenon are determined by the mean value of load/strain applied during fatigue. Under strain control, a positive mean strain leads to cyclic stress relaxation ( the hysteresis loop shifts in the direction to establish a zero mean stress). On the other hand, for an applied positive mean stress, cyclic creep would take place (shifting of hysteresis loop in the direction of positive strain), which would anticipate crack propagation and limit fatigue life (Dowling, 1993).
In the cases where initiation period represent a significant part of life to fracture, it is fundamental to analyze the transient period since, as in the case of HSLA steels, *the material may continue cyclic softening during all the initiation period* (Quesnel and Meshi., 1977). For these steels, cyclic softening is slow due to dislocation interaction with the steel microconstituent (precipitates and cementite plates). This paper analyses cyclic behavior of a low carbon steel under different prestrain histories, correlating hysteresis loop shape and substructure alteration.

## EXPERIMENTAL PROCEDURE

1012[1] low carbon steel plates were cold worked following two proportional and a non-proportional deformation paths: symmetric biaxial stretching, uniaxial tension and a mixed path including symmetric biaxial stretching and uniaxial tension. The samples had an initial and final thickness of 4.5 and 4.1 mm, respectively. Fatigue life testing was done by axially loading samples under strain control. Development of the dislocation substructure during the crack initiation period was determined by axially loading samples up to predetermined fractions of fatigue life. The applied strain range was 0.25% for both studies, and axial loading followed the rolling direction. Results were compared with the steel in the as hot rolled condition. Fatigue tests were repeated twice for each condition.

## RESULTS AND DISCUSSION

Figures 1 to 3 show the hysteresis loops for the steel in the as hot rolled and cold worked conditions. The figures show the life to fracture; the initial (i) and final (f) values for the maximum and minimum stress and the initial *ratio* of the mean stress ,$R_i$ , (defined as initial ratio of minimum to maximum stress). The final values of stress were registered just before the complete fracture of the sample. Independent of the strain history, the steel softens cyclically, as indicated by the gradual fall of the maximum stress during the initiation period. In general, the initiation period may be considered as the period during which the hysteresis loops are symmetrical (i.e, loop shape during loading and unloading remains the same)(Kilman and Bily, 1984). In the case of the hot rolled steel, cyclic softening is attributed to the annihilation and

[1] Steel plates rapidley cooled before coilling



rearrangement of the free dislocations present in the matrix after the thermo-mechanical processing of the steel. A significant distribution of free dislocations is expected in that steel since it was not post-annealed. Post annealing would minimize the density of these dislocations.

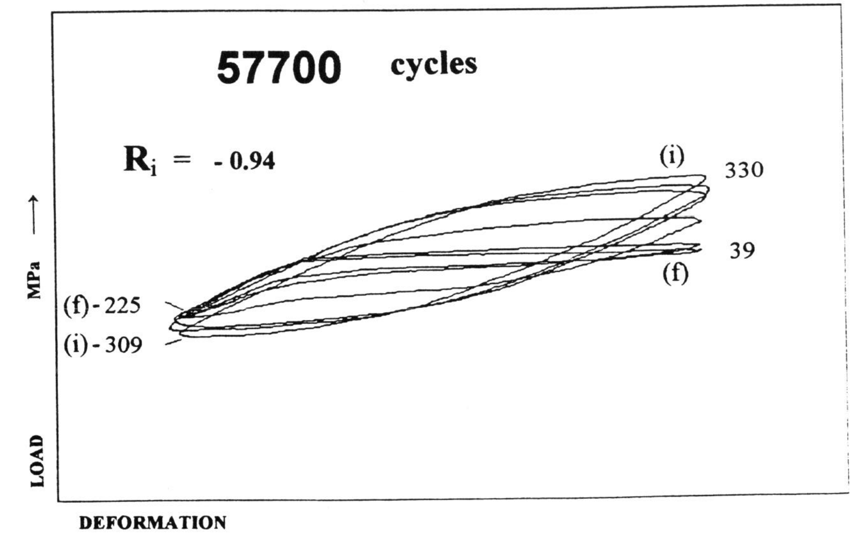



Fig. 1- Hysteresis loops for the hot-rolled steel

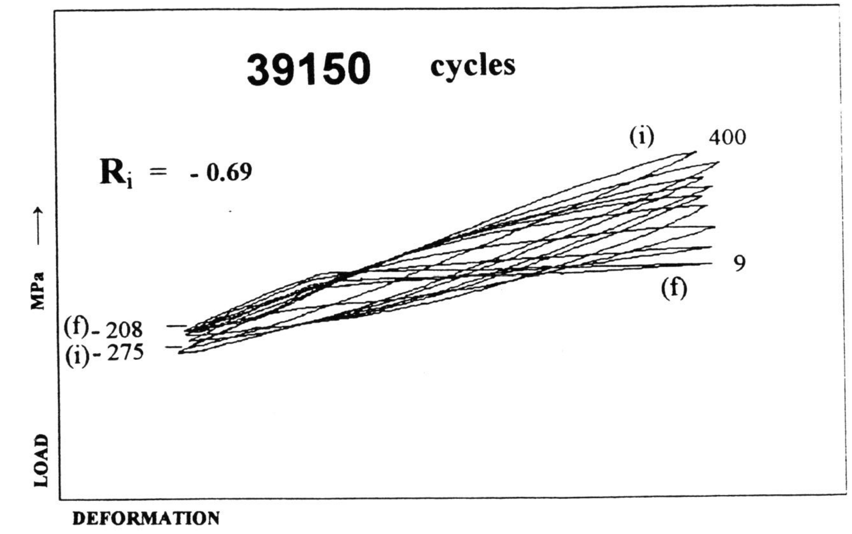



Fig. 2- Hysteresis loops for the cold stretched steel

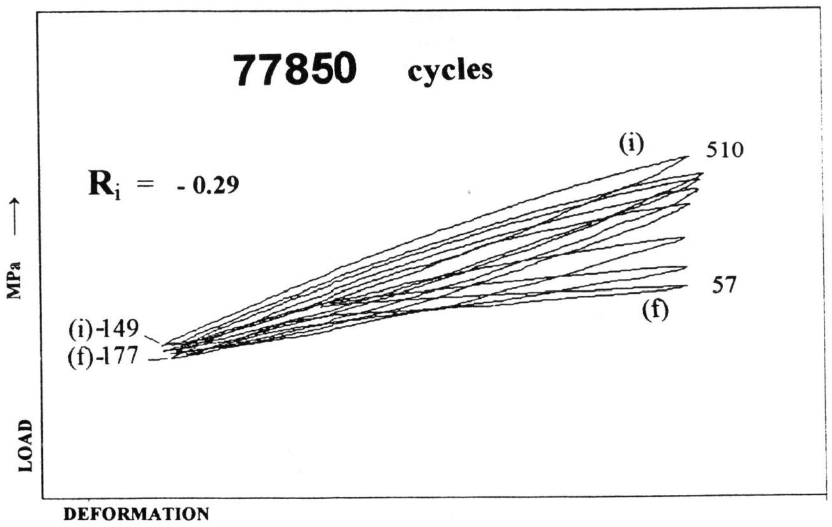



Fig. 3- Hysteresis loops for the uniaxially tensioned steel

### *Hot Rolled, Proportionally Stretched and Tensioned Steels*

The hysteresis loops of Fig. 1 and 2, show that besides the gradual fall of the maximum tensile stress, indicating softening, there is concurrently a gradual decrease of the maximum compressive stress (hysteresis loop rotates clockwise as cycling goes by). This indicates that, for the two steels, there is a tendency to maintain the initial mean stress. The initial values of the mean stress *ratio*, $R_i$ , are -0.94 and -0.60 for the hot rolled and stretched steel, respectively. In other words, the initial mean stress is near to zero for the hot rolled steel, while the stretched steel presents a positive mean stress. Dislocation movement is facilitated for a near zero mean stress (Quesnel and Meshi, 1977). On the other hand, a positive mean stress effectively imposes cyclic hardening in opposition to the material softening. This inhibits dislocation movement, resulting in a slower softening rate (Chai and Laird, 1987). Therefore, the rate of cyclic softening will be higher in the hot rolled steel than in the stretched steel. This difference in softening rate permits the hot rolled steel to attain cyclic stability faster. As explained by the following, the quickness in attaining cyclic stability favors a longer fatigue life for the hot rolled steel. First, we analyze the curves of rate of variation of maximum cyclic stress, Fig. 4. The gradual decrease and stabilization of the stress correspond to the period of crack initiation or the formation of a very small crack, and the final sharp slope correspond to the crack propagation period (El-Sharawy *et al.*, 1993). This definition assumes that the initial period of small crack propagation, which also reflects a gradual drop in tension, is limited. The curves show that, independent of the prestraining history, there is a small variation of the crack propagation period. Curves of crack propagation rate da/dN versus $\Delta K$ confirm this result (El- Sharawy *et al.*, 1993). Therefore, *for the cases studied*, the fatigue life is principally a function of the initiation period. Fig. 4 shows that the stress of the hot rolled steel converges rapidly to cyclic stability as indicated by the early formation of a platform. On the contrary, the stretched steel continues softening near to the end of the initiation period. During stability, plastic strain is accommodated through an equilibrium between the generation and annihilation of dislocations. While cyclic softening includes



principally annihilation of dislocations. In other words, throughout stability, when strain is almost reversible, cyclic plastic strain is exhausted at a slower rate than during softening. The curves show that the shorter transient period of the hot rolled steel correspond to a relatively small fraction of the crack initiation period. Therefore, the plastic strain exhausted during softening is also limited. Consequently, the bulk of strain will be exhausted at a slower rate throughout stabilization, which permits the prolongation of cyclic stability and the overall initiation period. On the other hand, if cyclic stability is retarded, as for the stretched steel, most of the plastic strain will be exhausted during the transient period. This may limit the subsequent period of cyclic stability, and the initiation period will be shorter. Since, for the cases studied, prior material history has a small effect on crack propagation, the effect of softening rate on the initiation period and, consequently, total fatigue life becomes prominent.

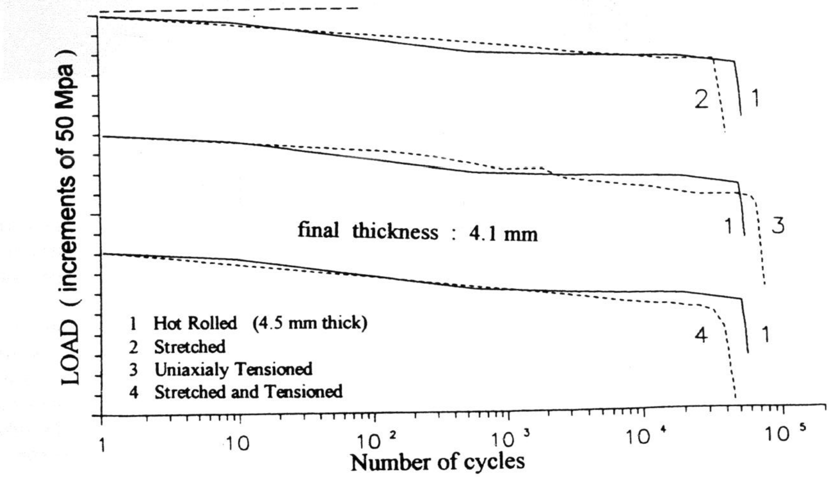
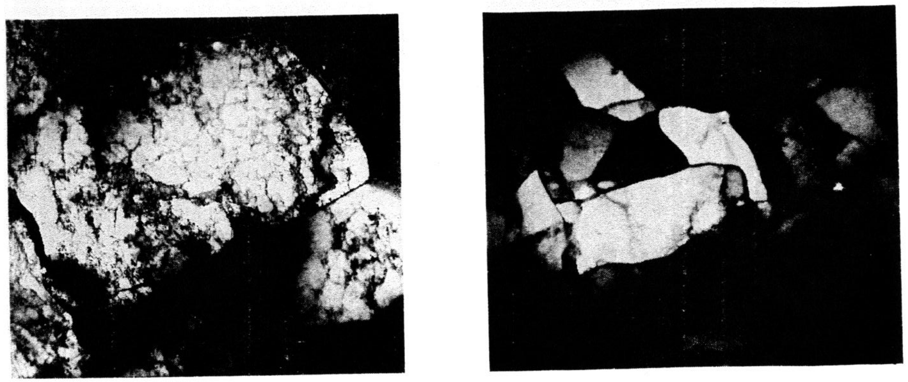
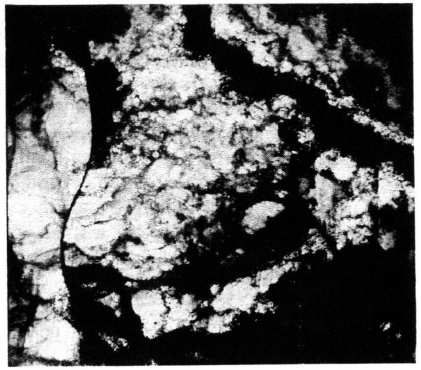



Fig. 4- Comparison of curves of rate of variation of maximum stress



a- before cycling b- after 12000 cycles

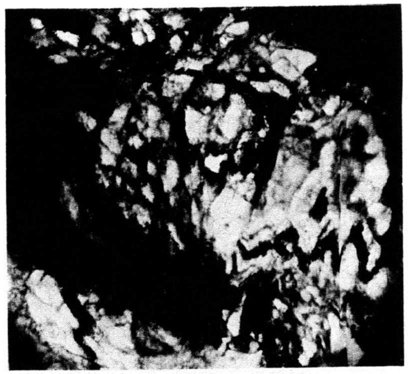
Fig. 5- Substructure development in the hot-rolled steel

a- before cycling b- after 10300 cycles

Fig. 6- Substructure development in the stretched steel

The development of the dislocation substructure during cycling confirms that the hot rolled steel converges quickly to the stabilized structure of coalesced and well defined cells, Fig.5, while the substructure of the stretched steel remains as ill defined dislocation cells after comparable periods, Fig. 6. All photographs represent the {112} crystallographic planes.
As explained by the following, the hysteresis loops should be correlated to the respective dilocations rearrangement. The loops for the hot rolled steel show a wider range of plastic strain and higher plastic energy (compare width and areas of loops, Fig. 1 and 2). Higher energy suggests a higher rate of exhaustion of cyclic plastic strain and, consequently, a shorter, and not, as obtained, a longer initiation period. However, as confirmed by the substructure development, the hot rolled steel quickly attains cyclic stability permitting the prolongation of the initiation




a- before cycling b- after 8000 cycles

Fig.7- Substructure development in the tensioned steel



period. Also, after cold working, the steel hardens cyclically and the hysteresis loops are narrower (El-Sharawy *et al.*, 1993). This suggests that the stretched steel would have a longer crack initiation period. Again, substructure analysis (retardation of dislocations rearrangement in this case) justified the obtained shorter initiation period. Therefore, separate analysis of the loops might lead to erroneous conclusions.
The hysteresis loops for the steel worked in uniaxial tension, Fig. 3, shows a lower range of applied plastic strain (narrower loops) than the hot rolled steel, and an initial mean stress ($R_i$ = -0.29). However, unlike the stretched steel, the initiation period is longer than that for the hot rolled steel. In this case, cyclic stress relaxation is taking place (hysteresis loop shifts in the direction of a zero mean stress), Fig. 3, which would facilitates dislocation movement (Quesnel and Meshi, 1977). Stress relaxation ***gradually*** opposes the effect of the initial positive mean stress and modest cell refining may be verified after 8000 cycles, Fig.7. Therefore, in this case, narrower cyclic plastic strain favors a longer initiation period than that for the hot rolled steel.

*Non-Proportional straining : Stretching - Tension*

Figure 8 shows that the substructure changes rapidly to coalesced cells with better defined boundaries. However, no additional refining was observed up to 11000 cycles (El-Sharawy, 1993). Despite the initially quick substructure alteration and a relatively rapid softening rate, Fig. 4, this steel continues softening during all the initiation period, without significant cyclic stability. Also, there is cyclic stress relaxation (El-sharawy, 1993) which, considering the reasoning adopted above, should facilitate dislocation movement and prolong initiation life. However, a simple comparison with the other steel histories is not plausible since, in this case, the prestraining path is non-proportional, and the effect of incremental plasticity should be considered. This contrasts with the above histories of proportional straining where only one prestraining path is acting. Nevertheless, important observations are made: 1- fatigue of the steel after nonproportional plastic straining may cause synergistic substructure alterations. 2- despite the rapid initial alteration, the development of a very well defined cellular structure is retarded, and fatigue life is not prolonged. This difference in fatigue behavior shows that the effect of combining stretching and tension is not equivalent to the sum of their separate effects.


a- before cycling b- after 940 cycles

Fig.8- Substructure development in the stretched and tensioned steel

*Curves of Rate of Variation of Maximum Stress*

The crack initiation period, defined from Fig.4 as the period of gradual decrease of maximum stress represents, independent of the prestraining history, the major part of life to fracture. The minimum crack initiation period (the stretched steel) is estimated to represent 75% of total fatigue life. The final sharp drop in stress (ranging 10000 cycles) defines the crack propagation period and shows that, *for the steel in consideration and the applied prestrain level*, the effect of the prestrain history is small. In general, and neglecting the gradual drop in stress at the beginning of propagation, these curves may be used to estimate the initiation and propagation periods of fatigue cracks.

## CONCLUSIONS

1- The low carbon steel may continue cyclic softening throughout most of the initiation period, and crack initiation occupied the principal fraction of fatigue life.
2- For the hot rolled steel, near to zero mean cyclic stress promotes cyclic softening and the substructure quickly develops into a well defined cellular structure.
3- Quick attainment of cyclic stability prolongs crack initiation period of the hot rolled steel.
4- mean cyclic stress and a wider range of applied plastic strain range accelerate crack initiation. While stress relaxation and a faster rate of substructure alterations prolong initiation period.
5- For the adopted level of proportional prestrain, the prestraining path has a small effect on the crack propagation period.
6- The combination of stretching and uniaxial tension has a synergistic effect on the substructure alteration during fatigue. However, the initial acceleration of dislocation rearrangement does not lead necessarily to an accelerated formation of a well defined cellular structure, and a prolongation of fatigue life.

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