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Research Paper

THE EFFECT OF HIGH CYCLE FATIGUE DAMAGE ON TOUGHNESS OF EN8 GRADE STEEL PART II

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Fatigue of metals is a subject of practical importance because many components and structures in service are subjected to varying loads and although the average stresses are often low, local concentration of stresses do not reduce the static strength but often lead to failure by fatigue. Micro-crack formation due to fatigue is more in ferritic-pearlitic annealed steel rather than in hardened and tempered steel with a structure consisting of tempered martensite along-with a little bit retained austenite. Fatigue striation density is more at a lower peak stress level as compared to a higher peak stress level fatigue.

Keywords: Fatigue damage, Toughness, EN8 grade steel

INTRODUCTION

Deformation during fatigue loading occurred earlier in ferritic-pearlitic annealed steel than tampered martensitic structure of hardened and tempered steel. The influence of grain size on the fatigue strength of steels is only of minor importance. Fine grained steels usually show a higher fatigue strength than coarse grained. The fatigue crack can propagate even at stresses below the fatigue limit (Ghosh *et al.*, 1989; and Talukdar, 1995). At the transit of the crack through the grain boundary, the stress necessary for crack propagation rapidly increases, that can be connected with the difference of orientation of neighboring grains and with the barrier effect of the grain boundaries. If this stress exceeds critical stress intensity, the crack will extend beyond the grain boundary and the second stage of its propagation begins (Forrest, 1962; and Talukdar, 1995). Change of the grain boundary has little effect on propagation of the fatigue crack in the second stage. The condition for the emergence of slip lines is influenced by the grain size, so the initiation of the crack, will be longer in structures of finer grains Forrest, 1962; Bruce, 1990; and Talukdar, 1995). Ferrite and pearlite grains as well as tempered

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martensite structure are normally refined for fatigue test at lower stress level. Elongation of individual grain is basically resumed in fine grain structure during fatigue deformation. Fatigue strength for materials of a cubic body centered lattice depends markedly on the grain dimension. The fatigue strength increases with decrease of grain dimension of ferrite in pearlite columns that shows the magnitude of ferrite region in pearlite has the same effect as the dimension of the pearlite in the matrix. A great number of experimental studies show that the grain dimension affects the fatigue strength without significantly affecting the fatigue crack propagation speed. The physical limit is a function of the formation of the hardened surface layer that is formed in the first moment of deformation. Loading at fatigue limit can cause the formation of fatigue cracks in this surface, but their size will not exceed the grain dimension due to the significant barrier effect of the grain boundaries (Lin and Ito, 1971; Pusker and Golovin, 1985; and Talukdar, 1995). Normally fatigue fracture zone is more in low stress level as when compared with high stress level and therefore fatigue striation density is also more in lower stress level fatigue loading. In general the effect of composition on fatigue strength is less important than the heat-treatment and microstructure. A structure consisting wholly of ferrite often has a fatigue limit greater than half its tensile strength but the strength is low whereas the best fatigue properties are obtained with tempered martensite. It has been suggested that the lower fatigue resistance of mixed structures may be attributed to "metallurgical notches" that might be coarse pearlite, free ferrite and retained austenite during quenching. The presence of about 10% of retained austenite reduces the fatigue strength (at 10^5 cycles) by 10-15% and greater quantities have little further effect. As the tempering temperature is raised both the tensile strength and fatigue strength reduce although the endurance ratio is usually increases (Dolan and Yen, 1948; Teed, 1950; Frankel *et al.*, 1960; Forrest, 1962; and Talukdar, 1995). In the present study fatigue tested (results are shown in Part I) and also samples of annealed and hardened and tempered En 8 steel are analyzed to characterize effect of fatigue stress on micro-structure and fracture behavior.

EXPERIMENTAL METHODS

The chemical composition of commercial grade En-8 steel is given in Part I (Table 1). The steel is received in the annealed condition. Macro-structure of fatigue fractured samples was taken in optical stereomicroscope. Optical micro-structure of annealed and hardened and tempered samples was taken after polishing and etching samples with 2% natal in Neophot microscope. Fractography of fatigue fractured samples were done in scanning electron microscope (JEOL Model JSM 840).

Table 1: Chemical Composition of En-8 Grade Steel

Chemical Composition	C (%)	Mn (%)	Si (%)	S (%)	P (%)
Standard	0.35-0.45	0.6-1.0	0.05-0.35	0.06 Max.	0.06 Max.
Present Experimental Steel	0.38	0.78	0.33	0.030	0.023

RESULTS AND DISCUSSION

Macro and microstructure photographs of annealed and hardened and tempered

Figure 1: Macro Photograph of Fatigue Failed (at 86 × 10^3 Cycles) Annealed Steel at 275 MPa Bending Fatigue Stress

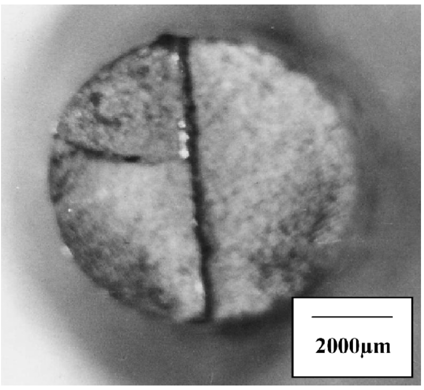


Figure 2: Macro Photograph of Fatigue Failed (at 4 × 10^3 Cycles) Annealed Steel at 437 MPa Bending Fatigue Stress

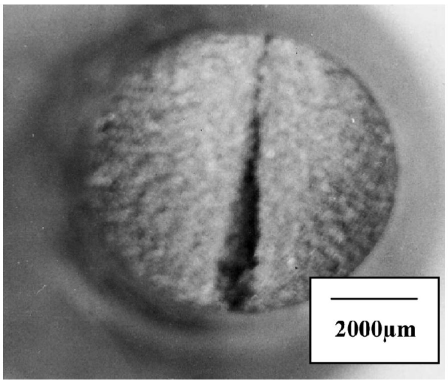


Figure 3: Macro Photograph of Fatigue Failed (at 73 × 10^3 Cycles) Hardened and Tempered Steel at 359 MPa Bending Fatigue Stress

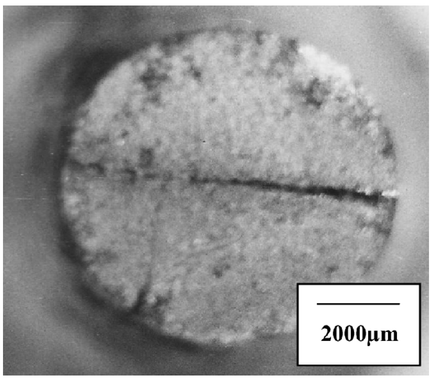


Figure 4: Macro Photograph of Fatigue Failed (at 78 × 10^3 Cycles) Hardened and Tempered Steel at 437 MPa Bending Fatigue Stress

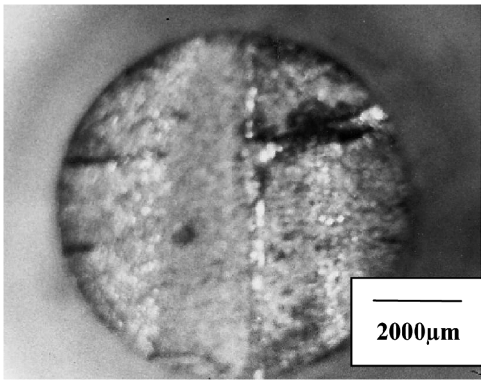


Figure 5: Macro Photograph of Fatigue Failed (at 10 × 10^3 Cycles) Hardened and Tempered Steel at 583 MPa Bending Fatigue Stress

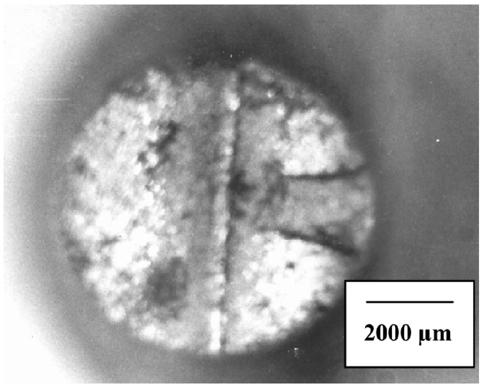


Figure 6: Optical Microphotograph of Fatigue Failed (22 × 10^3 Cycles) Annealed Steel at 384 MPa Bending Fatigue Stress

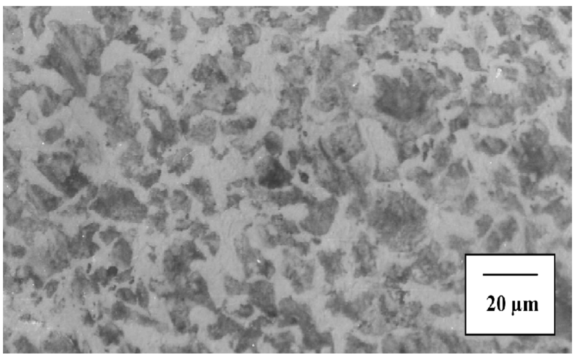


Figure 7: Optical Microphotograph of Fatigue Failed (at 6 × 10^3 Cycles) Annealed Steel at 730 MPa Bending Fatigue Stress

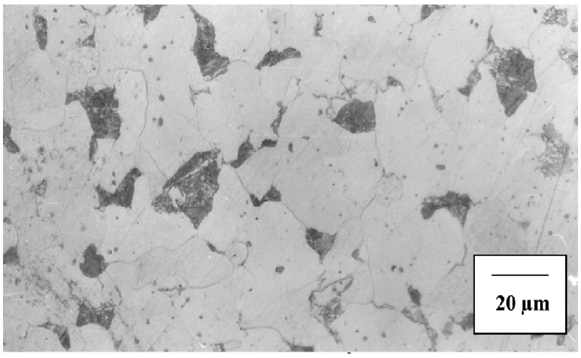


Figure 8: Optical Microphotograph of Without Fatigue Failure (Upto 10^7 Cycles) Annealed Steel at 191 MPa Bending Fatigue Stress

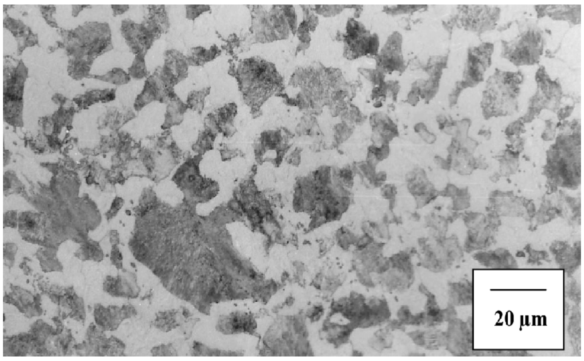


Figure 9: Optical Microphotograph of Fatigue Failed (Upto 73 × 10^3 Cycles) Hardened and Tempered Steel at 359 MPa Bending Fatigue Stress

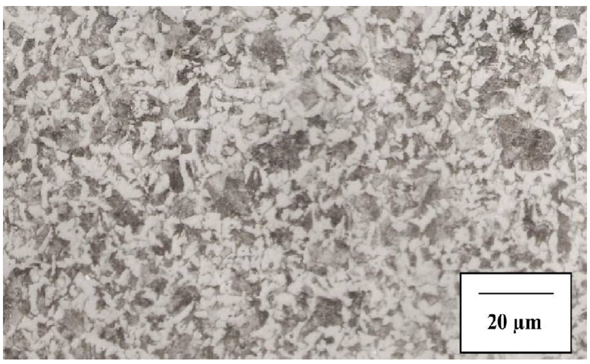


Figure 10: Optical Microphotograph of Fatigue Failed (Upto 3.5 × 10^3 Cycles) Hardened and Tempered Steel at 553 MPa Bending Fatigue Stress

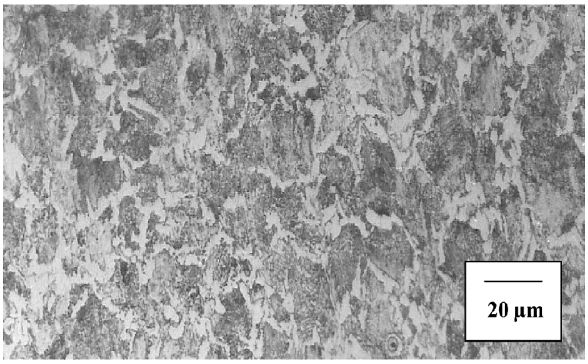
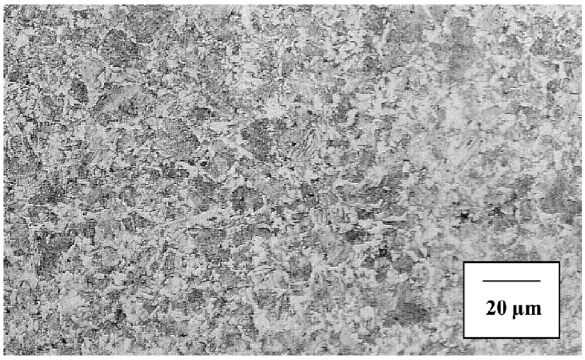


Figure 11: Optical Microphotograph of Without Fatigue Failure (Upto 1 × 10^3 Cycles) Hardened and Tempered Steel at 578 MPa Bending Fatigue Stress



steels are shown in Figures 1 to 11. Microstructures observation was done with the optical microscope (MeF2) for fatigue and without fatigue specimen. Macrostructure of fractured surfaces were also observed under stereomicroscope at low magnification (2000 μm).

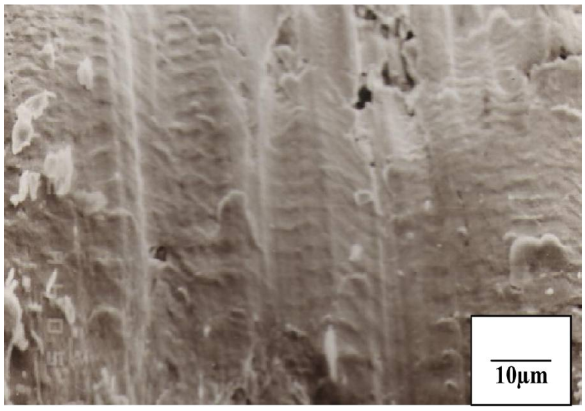
Macrostructure of fatigue tested annealed steels are shown in Figures 1 and 2 for stress levels of 275 MPa and 437 MPa. Fatigue fracture zone is more in low stress level, i.e., 275 MPa. Macrostructure of fatigue tested hardened and tempered steels are shown in

Figures 3 to 5 for stress levels 359 MPa, 437 MPa and 583 MPa. Here also fatigue fracture zone is more in low stress level, i.e., 359 MPa. Microstructures of annealed steel are shown in Figures 6 to 8 which indicate little bit deformation of ferrite and pearlite in annealed steel. This pearlite and ferrite grain size are refined when fatigue tested at lower stress level (384 MPa, Figure 6), but at higher stress level (730 MPa, Figure 7) the ferrite and pearlite grains are not refined and remain similar to cyclically non-deformed annealed steel. Optical Microphotograph (Figure 8) of without fatigue failure (up to 10^7 cycles) annealed steel at 191 MPa bending fatigue stress indicates some deformation in ferrite and pearlite grains. Tempered martensite structure after fatigue deformation indicates deformation in the form of elongation of individual grains. Microstructure of hardened and tempered steel after fatigue failure at 359, 553 and 570 MPa stress levels are shown in Figures 9 to 11. At lower stress level, i.e., at 359 MPa grains are much finer compared that at higher stress level, i.e., at 553 MPa.

Scanning electron microphotograph of annealed and hardened-tempered fatigue steel are shown in figures 12 to 17 respectively indicate that homogeneity of fine dimple structure in hardened-tempered steel where-as fatigue striation with tearing type of rupture in annealed steel.

Fractograph were done for fractured samples in overall as well as in between ductile and brittle zones. On a microscopic scale the observed fracture modes are cleavage, quasicleavage and dimpled fracture. Cleavage fracture, i.e., flat facets represent brittle fracture occurring along crystallographic planes, usually exhibit “river marking”. The river markings (Figure 12) are caused by the crack moving through the crystal along a number of parallel planes which form a series of plateaus and connecting redges. These are indications of the absorption of energy by local deformation. The direction of the “river pattern” represents the direction of crack propagation. Quasi-cleavage fracture is related but distinct to cleavage fracture. It is observed chiefly in low temperature fracture of quenched and tempered steels. Here the facets on the fracture surface are not true cleavage planes and the fractures often exhibit dimples and tear ridges around the periphery of the facets. Fatigue brittle fractures occur in a transgranular manner. Dimple rupture which denotes a ductile fracture is characterized by cup-like depressions that may be equiaxial, parabolic or elliptical. Microvoids are initiated at second phase particles, the voids grow and eventually the ligaments between the microvoids fracture. The fatigue fracture surface of stage II crack propagation frequently shows a pattern of ripples or fatigue striations. These striations show a wavy

Figure 12: SEM Fractograph on Interface Region of Fatigue Failed Annealed Steel (550 MPa, 7 × 10^3 Cycles)



pattern appearance on SEM fractograph. Extrusions and intrusions are seen as corrugated shape appearance with wavy pattern striations also on SEM fractograph in higher magnification. Fatigue fracture area is more in lower stress level (Figure 17). The fracture surfaces indicate that at lower stress level the ductile zone is more compared to higher stress level before occurrence of final failure. Secondary micro-cracks increase with fatigue cycles with an increase of cyclic stress range. The first stage of fatigue striation extension becomes short (Fan *et al.*, 2005). Micro-cracks also develop possibly at the initiating or first stage of fatigue deformation at high stress range (Defang, 1990).

Interface of brittle fracture and fatigue fracture zone of annealed steel after fatigue test at 637 and 550 MPa stress levels are shown in Figures 14 and 15 whereas final failure (brittle fracture) zone are shown in Figures 16 and 12. Much more tear out depth profile are there in the interface of high stress fatigue test specimen. Whereas density of

Figure 13: SEM Fractograph on Centre Region of Without Fatigue Failure Hardened and Tempered Steel (570 MPa, 1 × 10^3 Cycles)

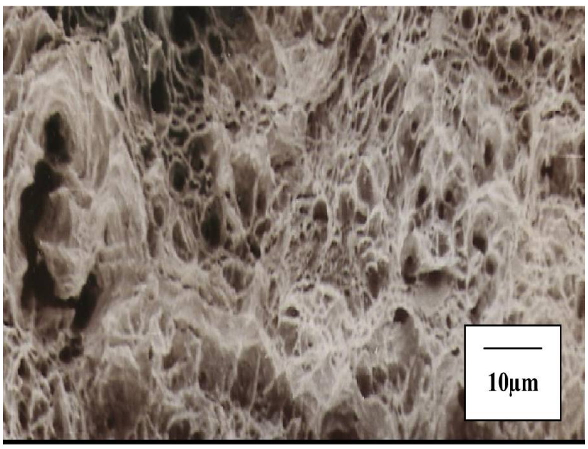


Figure 14: SEM Fractograph of Interface Region of Fatigue Failed (at 4 × 10^3 Cycles) Annealed Steel at Bending Fatigue Stress of 637 MPa

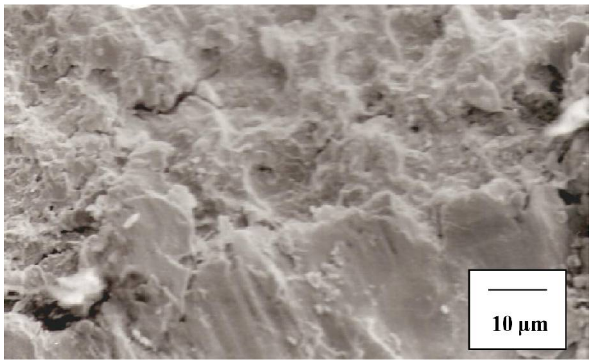


Figure 15: SEM Fractograph of Upper Region of Fatigue Failed (at 7 × 10^3 Cycles) Annealed Steel at Bending Fatigue Stress of 550 MPa

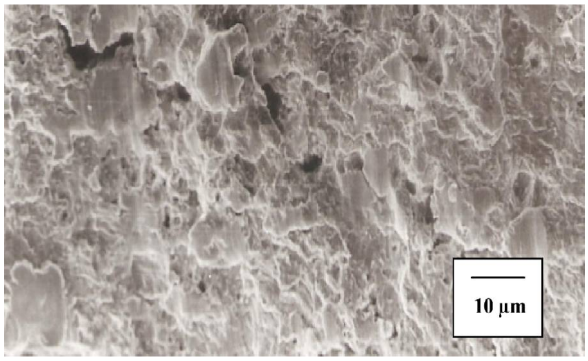
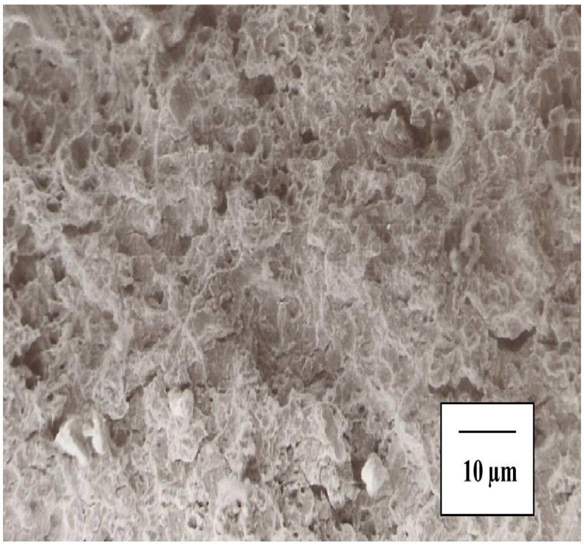


Figure 16: SEM Fractograph for Interface Region of Fatigue Failed (at 4 × 10^3 Cycles) Annealed Steel at Bending Fatigue Stress of 637 MPa

Figure 17: SEM Fractograph for Centre Region of Fatigue Failed (at 73 × 10^3 Cycles) Hardened and Tempered Steel at Bending Fatigue Stress of 359 MPa



fatigue striations are more in lower stress fatigue test specimens. In hardened and tempered steels size of dimples are smaller in the fatigue fractured specimen with lower stress level (359 MPa) fatigue test compared to higher stress level (570 MPa) fatigue test (Figures 13 and 17).

CONCLUSION

- Hardened and tempered steel has better fatigue endurance as compared to annealed steel for the presence of tempered martensite.
- Pearlite and ferrite grains of annealed steel are deformed to some extent and at lower stress level this pearlite and ferrite grain size are refined.
- Tempered martensite structure of hardened and tempered steel shows some deformation during fatigue loading in the form of elongation of individual grains.
- Fatigue fracture zone as well as density of fatigue striations is more in lower stress level as compared to higher stress level fatigue.
- Much more tear out depth profile are present in the interface of fatigue fracture zone and the parent metal at high stress fatigue cycling.
- Dimples are smaller in fracture zone of lower stress level fatigue loading of hardened and tempered steel.

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