Characteristics affecting each stage of fatigue fracture

This chapter presents fatigue of metals, stages in fatigue fracture and material characteristics affecting each stage of fatigue fracture. Further, relationship between the fatigue fracture and stress intensity factor has also been elaborated.

Keywords: Fatigue, stages of fatigue fracture, fatigue crack nucleation, stable fatigue crack growth, slip, stress intensity factor range, sudden fracture

The fluctuations in magnitude and direction of the load adversely affect the life and performance of an mechanical component compared to that under static loading condition. This adverse effect of load fluctuations on life of a mechanical component is called fatigue. Reduction in life of the mechanical components subjected to fatigue loads is mainly caused by premature fracture due to early nucleation and growth of cracks in the areas of high stress concentration occurring either due to abrupt change in cross section or presence of dis-continuities in form of cracks, blow holes, weak materials etc.

26.1 Fracture under fatigue loading

The fracture of the mechanical components under fatigue load conditions generally takes place in three steps a) nucleation of cracks or crack like discontinuities, b) stable growth of crack and c) catastrophic and unstable fracture. Number of fatigue load cycles required to complete each of the above three stages of the fatigue eventually determines the fatigue life of the component (Fig. 26.1). Each stage of fatigue fracture ranging from crack nucleation to catastrophic unstable fracture is controlled by different properties such as surface properties, mechanical and metallurgical properties of the components in question. Any of the factors related with material geometry of the component and loading condition which can delay the completion of any of the above three stages of the fatigue will increase the fatigue life.

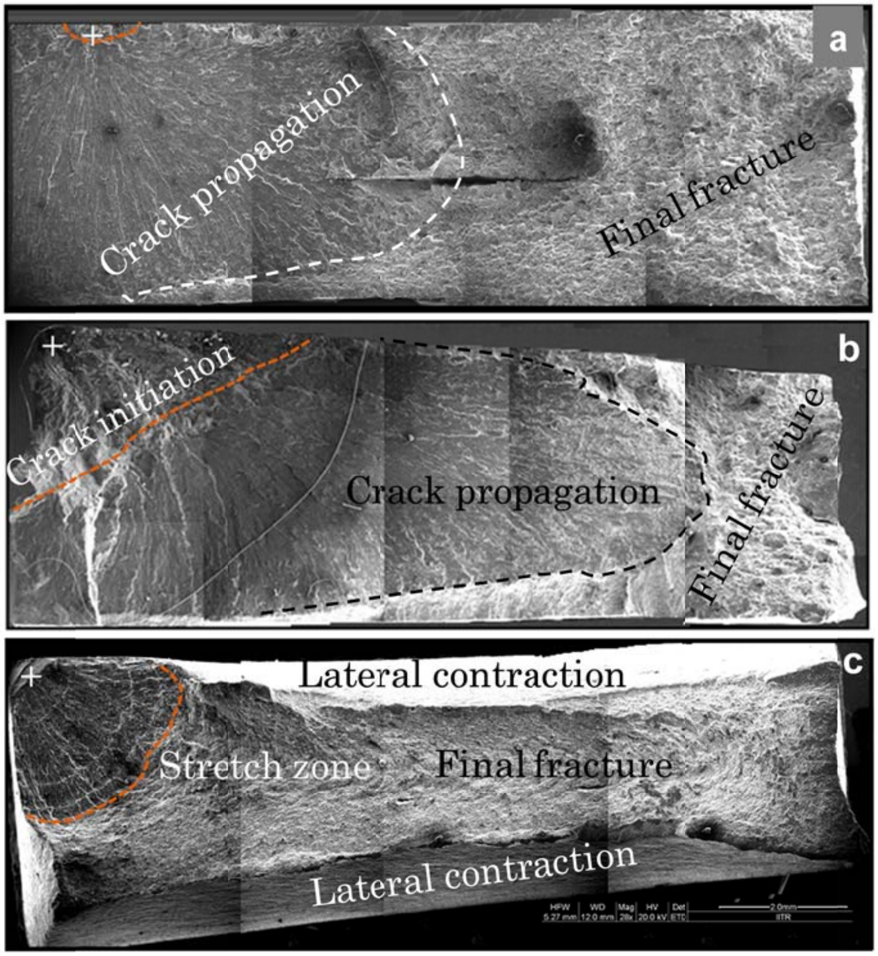

Fig. 26.1 Photograph of fatigue fracture surface of a weld joint

26.2 Factors affecting the stages of fatigue fracture

26.2.1 Surface crack nucleation stage

Surface crack nucleation stage is primarily influenced by surface properties such as roughness, hardness, yield strength and ductility of the engineering component subjected to fatigue provided there is not stress raiser causing stress localization. Cracks on the smooth surface of engineering component are nucleated by micro-level deformation occurring at the surface due to slip under the influence of fluctuating loads. Repeated fluctuation of loads results surface irregularities of micron level which act as stress raiser and site for stress concentration. Continued slip at certain crystauographic planes due to fluctuating load cycle finally produces crack like discontinuities at the surface. It is generally believed that first crack nucleation stage takes about 10-20% of total fatigue life cycle of the engineering component. Since the mechanism of fatigue crack nucleation is based on micro-level slip deformation at the surface therefore factors like surface irregularities (increasing stress concentration), high ductility, low yield strength and low hardness would facilitate the micro-level surface deformations and thereby lower the number of fatigue load cycles required for completing the crack nucleation stage (Fig. 26.2). Hence, for enhancing the fatigue life attempts are always made to improve the surface finish (so as to reduce stress concentration due to surface irregularities if any by grinding, lapping, polishing etc.), increase the surface hardness and yield strength and lower the ductility using various approaches namely shot peening, carburizing, nitriding, and other hardening treatment.

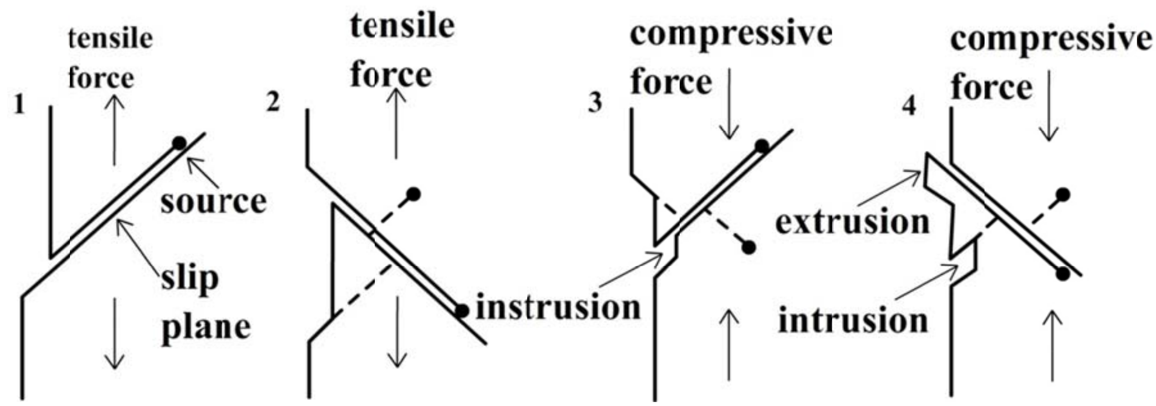

Fig. 26.2 Schematic of fatigue crack nucleation mechanism

Surface nucleation stage in case of welded joints becomes very crucial as almost all the weld joints generally possess poor surface finish and weld discontinuity of one or other kind which can act as a stress raiser. Further, the development of residual stresses in weld joints can also promote or discourage the surface nucleation stage depending upon the type of loading. Residual stresses similar to that of external loading facilitate the crack nucleation while that of opposite kind tends to discourage the crack nucleation. This is the reason why welding of base metal lowers the fatigue life up to 90% depending upon the type of the weld joints, loading conditions and surface conditions of weld.

26.2.2 Stable Crack Growth Stage

A crack nucleated in first stage may be propagating or non-propagating type depending upon the fact that whether there is enough fluctuation of load or not for a given material. A fatigue loading with low stress ratio (ratio of low minimum stress and high maximum stress) especially in case of fracture tough materials may lead to the existence of non-propagating crack.

However, growth of a propagating crack is primary determined by stress range (difference of maximum and minimum stress) and material properties such as ductility, yield strength and microstructural characteristics (size, shape and distribution of hard second phase particle in matrix). An increase in stress range in general increases the rate of stable crack growth in second stage of fatigue fracture. Increase in yield strength and reduction in ductility increase the crack growth rate primarily due to reduction in extent of plastic deformation (which reduces blunting of crack tip so the crack remains sharp tipped) experienced by material ahead of crack tip under the influence of external load. Increase blunting of crack tip lowers the stress concentration at the crack tip and thereby reduces the crack growth rate while a combination of high yield strength and low ductility causes limited plastic deformation at crack tip which in turn results in high stress concentration at the crack tip. High stress concentration at the crack tip produces rapid crack growth which reduces number of fatigue load cycle (fatigue life) required for completion of second stage of fatigue fracture of component.

All the factors associated with loading pattern and material which increase the stable crack growth rate, lower the number of fatigue load cycle required for fracture. High stress range in general increases the stable crack growth rate. Therefore, attempts are made by design and manufacturing engineers to design the weld joints so as to reduce the stress range on the weld during service (of possible) and lower the crack growth rate by developing weld joints of fracture tough material (having requisite ductility and yield strength).

The fracture mechanics principles have also been applied in fatigue studies to understand the conditions required for different stages of fatigue. The fracture mechanics considers the materials properties, crack size and applied stress condition for suggesting the conditions for growth of crack under fatigue condition. One of common terms in fracture toughness is stress intensity factor indicating the stress intensity near the tip of crack and is extensively used to predict the crack propagation and fracture conditions in case of homogeneous, linear elastic material for providing a failure criterion for brittle materials. Stress intensity factor (K) under uni-axial stress condition is given by $\sigma(\pi c)^{1/2}$. Where σ is applied stress (MPa), π is the constant, c is length (in m) of surface crack (half crack length of crack insides the body). For a given crack length, under varying load conditions stress intensity factor varies from max to min level as per externally applied stress. The variation in stress intensity factor is called stress intensity factor range (ΔK). A minimum stress intensity factor range needed for commencement of propagation of the crack is called threshold stress intensity factor (ΔK_{th}) as shown in Fig. 26.3. The Paris law shows the relationship between the stress intensity factor range (ΔK) and crack growth rate (dc/dN) per load cycle in second stage of fatigue fracture and is expressed as below.

Crack growth rate (dc/dN)= $C(\Delta K)^m$

Where c is the crack length, *N* is the number of load cycles and m is slope of curve in stage 2 of crack growth (Fig. 26.3).

26.2.3 Sudden fracture (Unstable crack growth)

Third of stage of fatigue fracture corresponds to unstable rapid crack growth causing abrupt facture. This stage commences only when load resisting cross sectional area of the engineering component (due to stable crack growth in second stage of fatigue fracture) is reduced to such an extent that it becomes unable to withstand maximum stress being applied during service. Hence, under such condition material failure occurs largely due to overloading of the remaining cross-section area. The mode of fracture at the third stage of fatigue failure may be ductile or brittle depending upon type of the material. Materials of high fracture toughness allow second stage stable crack growth (of fatigue fracture) to a greater extent which in turn delays the commencement of third stage unstable crack propagation (Fig. 26.3). Conversely for a given load, material of high fracture toughness (high strength and high ductility) can withstand to a very low load resisting cross sectional area prior to the commencement of third stage of fatigue failure than that of low fracture toughness matel.

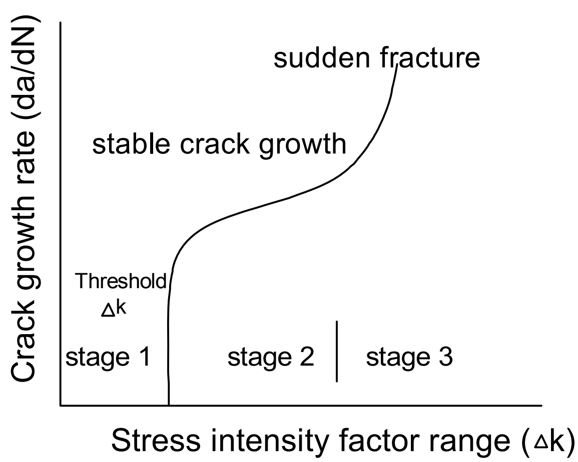

Fig. 26.3 Stage II stable fatigue crack growth rate vs stress intensity factor range in fatigue test.

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