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Fatigue Life Dependency on the Cleanliness and Ductility of Structural Steels

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Abstract: Plain concrete is very brittle and weak. It cannot withstand sudden shock, cyclic load and high level of tensile stress. So, concrete is reinforced by various types of structural steels. To reduce the overall weight of the RCC structures, worldwide practice is to use high strength structural steels along with high strength concrete. In this research work low strength high ductility (300 grade) and high strength moderate ductility (500 grade) locally produced steel bars of 20mm diameter were used. They were then characterized by means of chemical composition, microstructure, size and distribution of inclusion particles, tensile and fatigue tests. The fracture surfaces of the failed fatigue samples were observed under optical and scanning electron microscopes. After detail investigation, experimental results suggest that compared to ductility, cleanliness of the structural steel bars are much more important for better fatigue life of the RCC structures.

1. Introduction

Steel has been used for many decades in structural and engineering purposes, both in land and marine environments, because of its good combination of mechanical, physical and chemical properties. There are many structures that are continuously under cyclic or fatigue loading conditions as bridges, flyovers, runways, jetties, etc. During earthquake all types of structures also face cyclic loading. There is no doubt that, for any RCC structure to be earthquake resistant the ductility of reinforcing materials used for the structure play a vital role [1-3]. In this regard, the qualities of compressive load bearing materials of the concrete such as cement, gravel, sand, etc. are also very important [4,5]. For a particular earthquake, the frequency, intensity and number of vibration depend on the nature of the earthquake. However, it is well established that the loading effects caused by any earthquake are very similar to that of cyclic or fatigue loading. So, use of structural steels having higher strength or high tensile ductility but low resistance to fatigue is not a good choice for earthquake resistant structures. Because of similar loading behaviours, both mechanically simulated fatigue loading and shaking by earthquake induced cyclic loading actions seem to be similar [1]. On the other hand, higher energy dissipation means better earthquake resistance, which is ultimately controlled by both the level of ductility and strength of the material considered. At the same time, ductility also controls the bendability, which is another key property for the earthquake resistant reinforcing steel bar [6-9]. In steels, there always exist a large number of inclusions, which degrade their fatigue lives [10], because the presence of inclusions deteriorates the bending and rebending properties of the rebars.

In Bangladesh, many structural design engineers believe that low strength steel bars as 300 and 400MPa grades having higher level of tensile ductility are more fatigue resistant, i.e. more earthquake safe. The aim of this research work is to discuss the effects of inclusions and tensile ductility on the total fatigue life of locally produced 300 and 500MPa grades of steel bars.

2. Materials and Experimental Procedure

The materials used in this research work were locally produced conventional low (300MPa) and high strength TMT (500MPa) steel bars of diameter 20mm. After collection, they were cut into two different sizes as ½ inch and 12 inch. For metallography and chemical analysis ½ inch length samples were used, whereas, for tensile and fatigue testing 12 inch long samples were used. In order to know the microstructures of the steel bars, metallographic samples were prepared for study under metallurgical microscope following standard procedure. After complete polishing, the faces of each sample were etched by 2% Nital solution. For all cases, metallography was performed on both unetched and etched samples. Using 500kN capacity Universal Testing Machines (Shimadzu, Japan) tensile tests were performed. Fatigue tests were conducted on Servo Hydraulic Fatigue Testing Machine (Instron, USA) of Model No.8801 of 100kN capacity. Here, required load (variable), frequency (70Hz), span length 160mm and stress ratio (0.1) were adjusted for each sample tested under compression-compression type loading mode. The collapsed (half broken) samples were forced for complete separation into two halves. Fracture surfaces were then photographed under optical and scanning electron microscopes to know various fracture features.

3. Results and Discussion

3.1. Chemical compositional analysis

The average chemical compositions of these steels are shown in Table 1.

Table 1. Chemical compositions of the steel bar used.

Sample ID	C	Si	Mn	P	S	Cu	Ni	Cr
300 MPa	0.21	0.44	0.93	0.064	0.081	0.134	0.052	0.151
500 MPa	0.18	0.24	0.94	0.041	0.033	0.203	0.031	0.084

From Table 1, it is clear that both grades of bars are of C-Mn structural steels. Here 500MPa steel bars conform to the ASTM Standard Specifications, however, 300MPa grade bars do not conform because of their higher level of phosphorus and sulfur contents [10]. Here it is be mentioned that these two elements are very detrimental for the fatigue properties of the steel bars as they make the bars brittle and crack sensitive because of their tendency to segregate at grain boundaries [11,12]. The structural steel bars of secondary steel routes are made by melting steel scraps, sponge irons, cast irons, etc and refining the molten steel to the required level. It is of note worthy that in Bangladesh almost all steel companies are using induction furnace melting process, which is really melting furnace rather than used for steel refining by international communities. From this melting route, to some extent, quality steel is possible if high grade steel scraps are used as input materials and the molten steel thus produced is further refined using ladle refining furnace. However, this practice is almost absent here.

3.2. Metallographic observation

The photomicrographs of various steel bars in unetched condition are presented in Figures 1 and 2. During the steel melting process, lots of fluxing agents along with other additives are added to the molten steel to adjust its chemical compositions within the prescribed range of the standard. These additives also produce slag that tries to float from inside the molten steel towards its surface. Moreover, oxides, dust particles and other nonmetallic components also produce additional slag and floats towards the surface. If sufficient time is not allowed for the inclusions to float to the top of the

IOP Conf. Series: Materials Science and Engineering **438** (2018) 012021 doi:10.1088/1757-899X/438/1/012021

molten steel, the inclusions will remain as a part of the steel matrix. The usual practice of production of TMT 500MPa grade steel requires refined steel billets. From Figure 1, it is clear that the inclusion level of this steel bar is very low. Moreover, particles sizes of inclusions are also small and they are well distributed. In the case of refining, argon gas is passed from the bottom of the ladle refining furnace, which helps break down the lump of the inclusions and distribute them in the molten steel. Argon gas flow also helps float the slag from inside the molten steel to the surface making overall inclusion content lower.

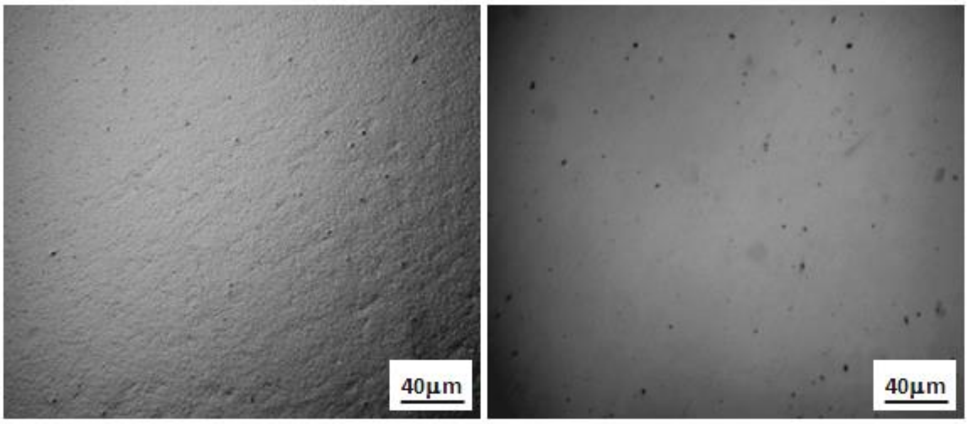


Figure 1. Photographs on unetched samples of 500MPa grade steel bars.

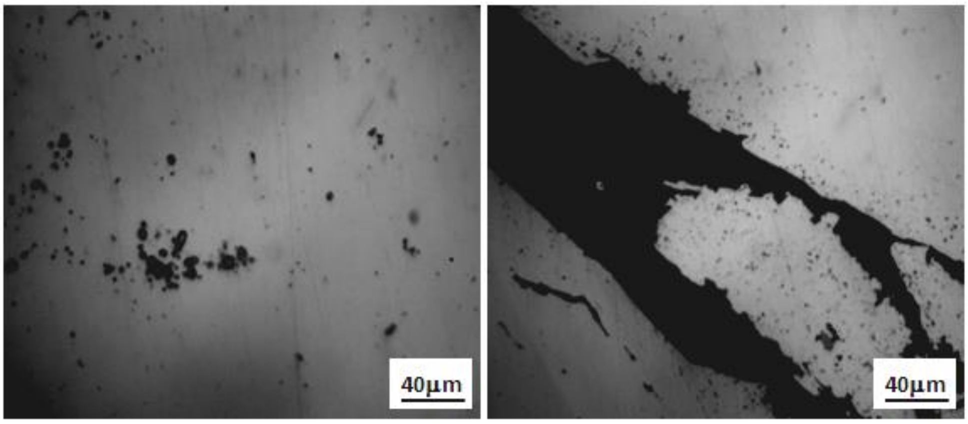
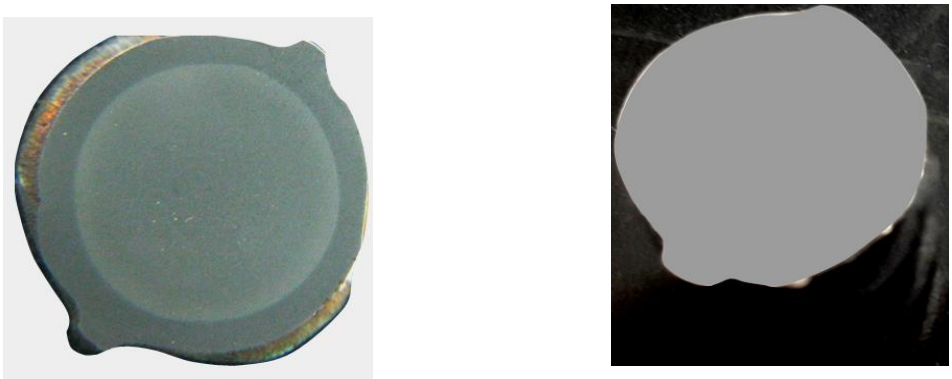


Figure 2. Photographs on unetched samples of 300MPa grade steel bars.

Micrographs presented in Figure 2 were taken on the unetched samples of 300MPa grade bar. These micrographs revealed somewhat more inclusion particles, which are also coarser in sizes. This is nothing but the result of insufficient refining and/or argon gas blow. In some samples very long and thick inclusion particles are also present in the steel bars. These types of inclusions are very dangerous for mechanical properties, especially, for cyclic property if they are unfortunately present at the critical location of the loaded steel bars. So, it is a great concern for the safety of any structures also if these bars are used [13-15]. Figure 3 confirmed that the 500MPa grade bar was of TMT process (presence of outer ring, left), whereas, identical surface throughout the whole section indicates that 300MPa bar was made via hot rolling and normalizing process (right side macrograph). Tempered martensitic case and fine grained ferrite-pearlitic core microstructures TMT 500MPa bar are shown in Figure 4.



(a) (b)

Figure 3. Macrophotographs showing etched surfaces of (a) 500MPa and (b) 300MPa bars.

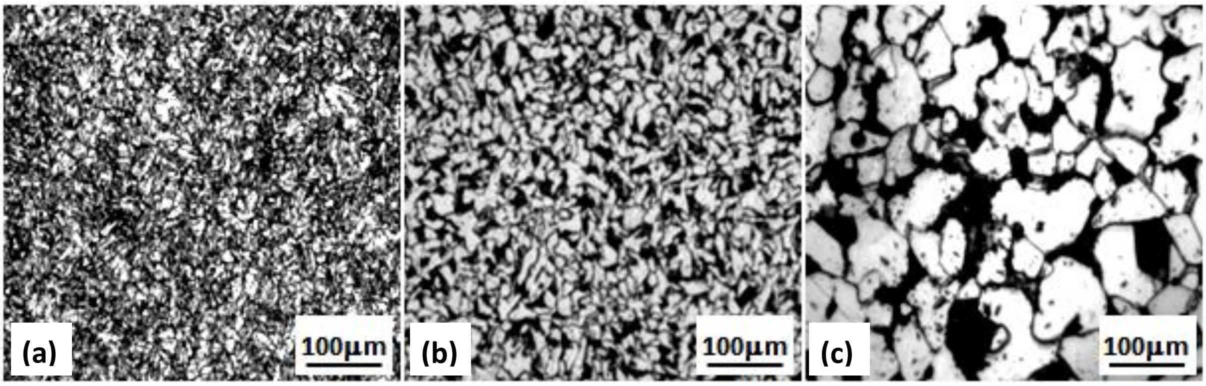


Figure 4. (a) Tempered martensites at the case, (b) ferrite-pearlite at the core of 500MPa bar and (c) ferrite-pearlite microstructures of 300MPa bar.

On the other hand, 300MPa bar is usually cooled in the open air after the completion of the hot rolling process. As a result, both the outer layer and inner core became to be composed of similar type of ferrite-pearlite microstructures, Figure 4c. The unetched micrographs revealed a huge amount of inclusion particles in 300 grade steel bar, which was very low for 500MPa bar (Figures 1 and 2). The etched micrographs presented in Figure 4 also confirm the similar observation. For 300 grade bar, especially, in the ferrite grains lots of black dots are visible which indicate the presence of coarse and overall huge amount of inclusion particles in the steel, but in the case of 500 grade bar this is almost absent.

3.3. Tensile behaviours

Following standard procedure tensile tests of steel bars were carried out on computer controlled 500kN capacity Universal Tensile Testing Machine. For all cases, at least, three samples were tested and the average values are presented in Table 2.

Table 2. Average tensile properties of the steel bar tested.

Sample ID	YS MPa	Ave YS MPa	UTS MPa	Ave UTS MPa	%El	Average
	312		481		17	
300 MPa	420	364	539	497	24	21
	360		473		22	
	520		621		16	
500 MPa	543	541	636	644	15	15
	560		675		13.5	

From Table 2, it is revealed that all steel bars provide the minimum levels of yield strength and ductility to satisfy the standards. Having almost similar chemical compositions, the production technologies made the bars of different grades.

3.4. Fatigue behaviours

Using the three point bend configuration, fatigue crack propagation tests were performed. Both fatigue cracking and crack growth tests to final failure were carried out at room temperature in the laboratory air on the same machine. Here, the total cycles elapsed for fatigue cracking and crack growth up to the final collapse of the as received samples were considered as the total fatigue life of individual test sample in different groups. The fatigue load versus fatigue cycles curves are shown in Figures 5-10.

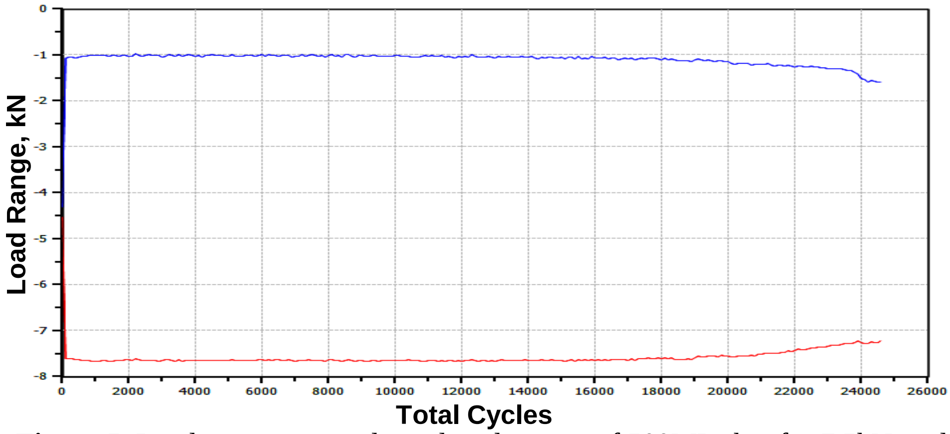


Figure 5. Load range versus elapsed cycle curve of 500MPa bar for 7.5kN set load.

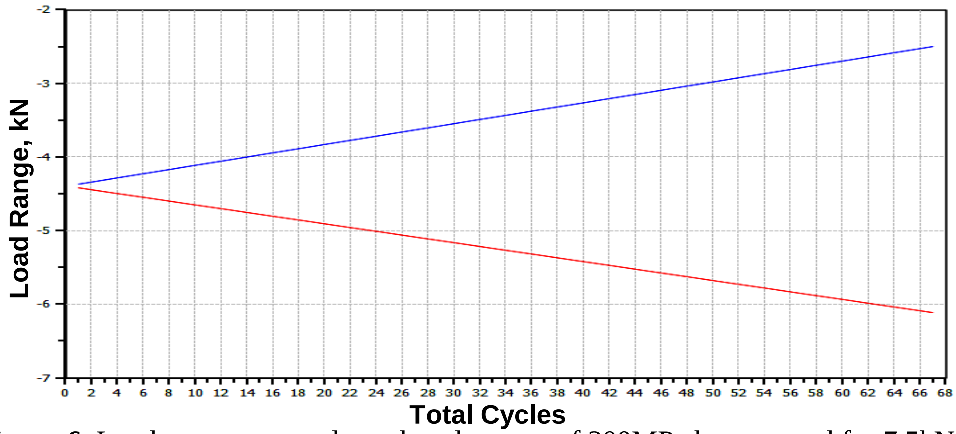


Figure 6. Load range versus elapsed cycle curve of 300MPa bar targeted for 7.5kN set load.

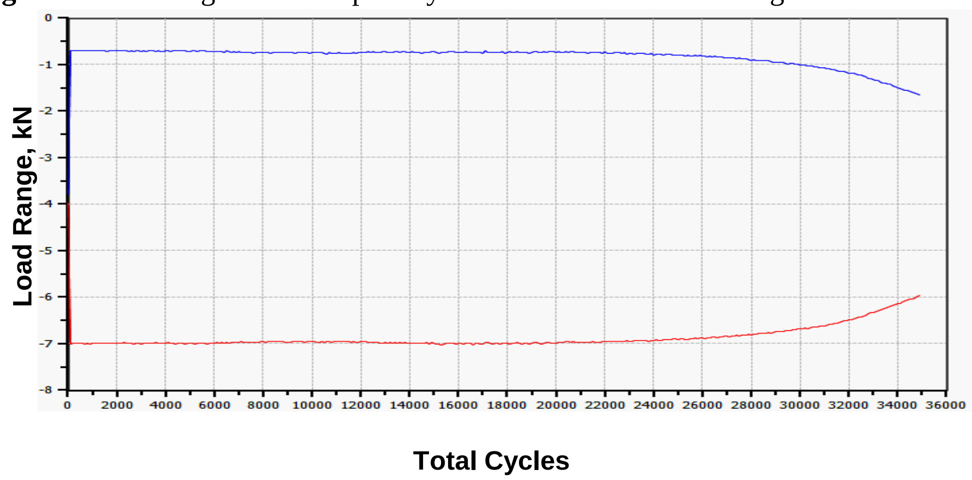


Figure 7. Load range versus elapsed cycle curve of 500MPa bar for 7.0kN set load.

IOP Conf. Series: Materials Science and Engineering **438** (2018) 012021 doi:10.1088/1757-899X/438/1/012021

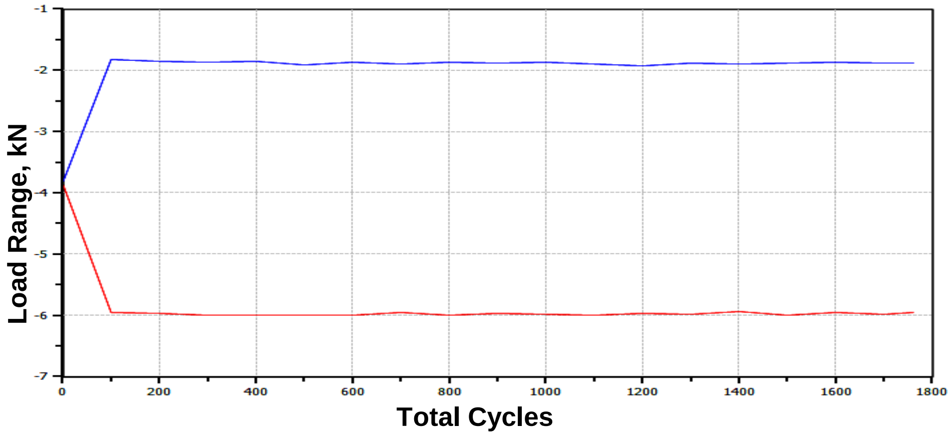


Figure 8. Load range versus elapsed cycle curve of 300MPa bar targeted for 7.0kN set load.

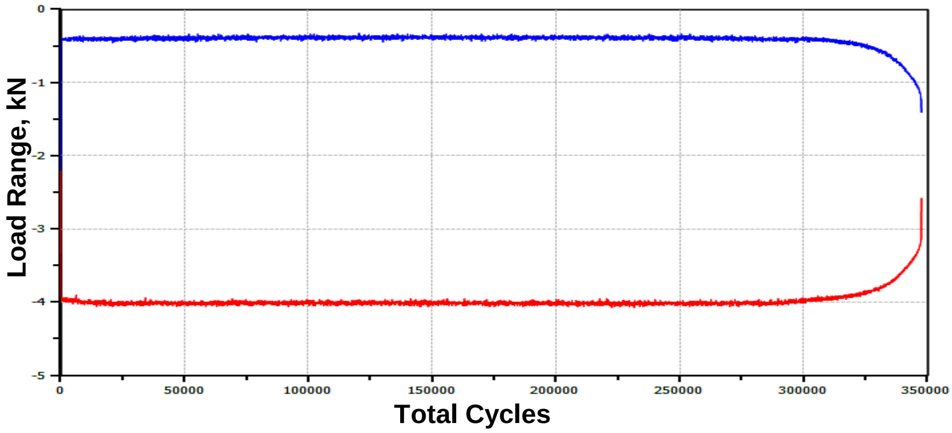


Figure 9. Load range versus elapsed cycle curve for 500MPa bar for 4.0kN set load.

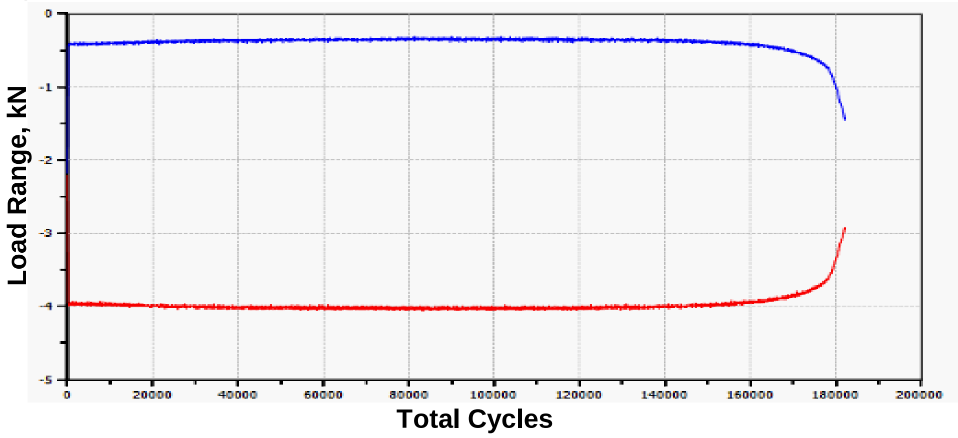


Figure 10. Load range versus elapsed cycle curve of 300MPa bar for 4.0kN set load.

Consider the cases at around 7.5kN (375MPa stress range) load, where 500 and 300 bars failed after, respectively 24500 and 66 cycles. At the same time, one very alarming observation is that, for 300MPa bar, the load was not possible to increase beyond 6.0kN (230MPa stress range), although the targeted load was 7.5kN. At reduced applied load of 7kN (321MPa stress range), bars of both grades tolerated higher levels of cycles. However, fatigue life of 300MPa bars is still alarming, which is only around 1800 cycles. The deterioration of fatigue resistance of 300 grade steel bars is mostly related to the inclusion content as well as higher level of trace elements sulphur and phosphorus in this grade of steel bars. Other researchers have also investigated the effects of trace elements and non-metallic inclusions on toughness and fatigue load tolerance and found severe degradation effects [11-13,16-19].

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As per their observation, inclusions are detrimental for fatigue properties, although their harmful effects may vary widely. In the case of lower level of applied load, which is experienced for high cycle fatigue, e.g. 400kN (144MPa stress range) load in the present work, the performance of the 300 grade bar is still not good, Figs.9-10.

As mentioned earlier, the presence of inclusion particles is not good for both toughness and fatigue resistance of steels. Whatever may be the nature of the non-metallic inclusions, they deteriorate the fatigue life of steels by accelerating the crack formation and growth, Figure 11. This overall scenario makes an early failure. This type of deterioration increases with increase in the area fraction of the non-metallic inclusions.

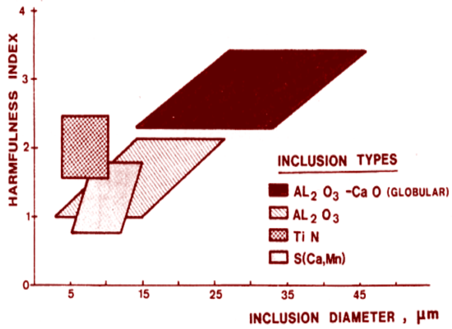

Figure 11. Harmfulness index of various inclusions on fatigue life.

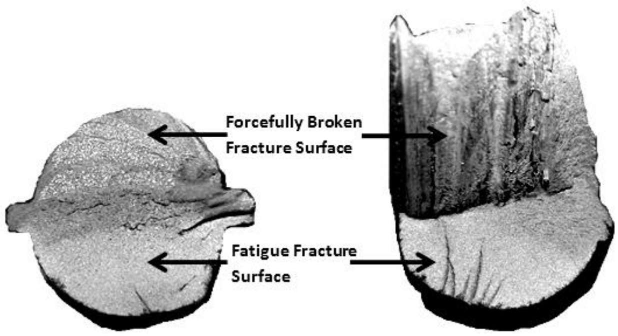

Figure 12. Low magnification fatigue fracture surfaces of 500 (left) and 300 (right) steel bars.

Inclusion particles were very frequently observed in the microstructures of 300 grade bars. Not only inside of the bars, they are also present at the surface and sub-surface areas that helped nucleate fatigue crack from the critical loading area, i.e. from the surface. Because of high volume fraction and closely spaced inclusions, along with segregation of trace elements sulphur and phosphorus fatigue cracks were initiated from multiple locations for 300 grade bar, they were then merged quickly that caused the bar to collapse very suddenly, which is clear from the fracture pattern of this steel bar, Figure 12.

Experimental results clearly revealed that both steel bars passed the tensile test requirements, however in fatigue tests, absolutely upsetting results have been observed for 300 grade bars. Now, why is this different behaviour of 300 grade bars? In tensile test, applied fully axial load is uniformly distributed on whole cross section, Figure 13. Because of loading scenario, in a particular section (marked blue dotted line), stress becomes uniformly active at the same time. If inclusion zone is considered as broken/weak ligament, then metallic portion bears most of the applied tensile load. So, inclusions become less sensitive for tensile test. However, in fatigue test bending stress becomes operative, where surface is the most critical zone, Figure 14. If there is any inclusion particle on the surface or subsurface areas, it instantly acts as a crack initiator and/or propagator and the surrounding metal cannot be as helpful as in the case of tensile loading to stop the crack formation or propagation.

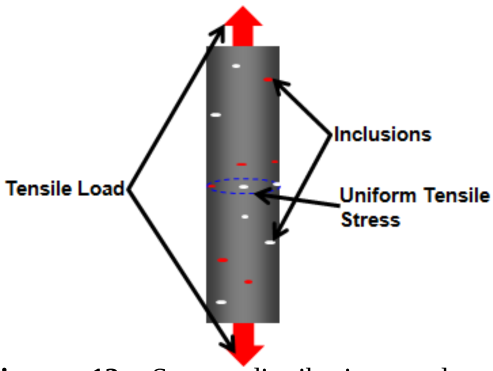

Figure 13. Stress distribution and concentration in tensile testing.

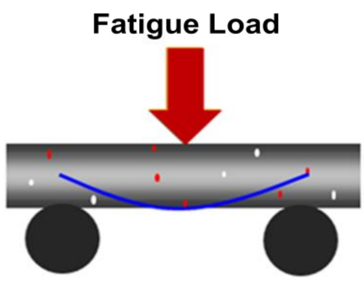

Figure 14. Stress distribution and concentration on the steel bar in bending-bending type fatigue testing.

4. Conclusions

After detail experimental studies on locally produced 300 and 500MPa grade steel bars, the following conclusion are drawn:

a. The chemical compositions of 300MPa grade bars are not controlled enough to meet the standard specification because of higher level of P and S contents.

b. At higher load, 300MPa bars collapsed almost instantly, whereas 500MPa bars withstand several thousands of cycles. At low load condition, both types of steel bars showed higher fatigue life, however, 500MPa bars showed significantly better performance for all cases.

c. Fractographic observation revealed that the worst fatigue lives and occasionally, the instant collapse of the 300MPa bars are very much related to the densely populated large size inclusion particles at the highly tensile critical location of the surface and also due presence of high percentages trace elements like S and P.

d. It is thought that steel bars with higher tensile ductility provide better toughness and fatigue life. However, present experimental results revealed that the higher ductility obtained via tensile test alone is not sufficient to provide better fatigue life, for which volume, size and distribution of inclusion particles play more vital role.

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