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Metallographic Failure Analysis on Bucket Elevator Conveyor Chain Links

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Abstract
Failure analysis is a critical process aimed at determining the root cause of every failure. Failure of conveyor chain links in the industry has many repercussions which include; uncsheduled down - time which reduces production time coupled with damaged buckets and chain links which increases maintenance and repair cost. Failure of conveyor chain links and engineering structures on a whole is inevitable and for this reason, carrying out an investigation aimed at determining the root cause of failure is very crucial in that it can either minimize or prevent future reoccurances. Visual examination, chemical analysis and metallographic analysis were performed on both failed and un - failed conveyor chain link samples. Visual examination revealed that the type of failure was brittle fracture in that there was no necking. In addition, visual examination reavealed that there was an offset between the sprockets evidenced by indentations on the outer link of the chain link as well as vibrations within the bucket elevator system. Also, the point of fracture initiation was dependant on where the inclusions which were the cause of failure were located; either at the core or at the boundary surafce. Chemical analysis performed established that Silicon (Si), Phosphorus (P), Sulphur (S), Manganese (Mn), Chromium (Cr) and Molybdenum (Mo) all met the British standard EN 10293 requirement for steel casting for engineering use but Carbon (C) did not. Metallographic analysis carried out on the conveyor chain links showed that the cracks had initiated from dissolved micro - inclusions and were therefore the root cause of failure. It was therefore established that brittle fracture induced by inclusions was the root cause of failure of the conveyor chain links. In order to nullify the effect of the micro - inclusion, it was recommended that a stress concentration factor for inclusions should be introduced in the design of these conveyor chain links so as to improve on their fatigue life.

Keywords: *Analysis, Bucket Elevator, Conveyor Chain links, Inclusions, Failure, Metallography.*

INTRODUCTION

It is often stated that history repeats itself but designers, manufacturers, and users do not want a repeat of history when it comes to the failure of components and equipment. The consequences and costs of fractured, cracked, corroded, and malfunctioned equipment are unwanted, dangerous and expensive. Throughout the years at East African Portland Cement, history has demonstrated that failure of conveyor chain link do occur. Data compiled for the last five years from 2012 to 2016 is as shown in Table 1.

Table 1: *Historic failure data on conveyor chains obtained from East African Portland cement.*

Year	Frequency of Failure
2012	33
2013	38
2014	41
2015	47
2016	50

Table 1 shows that for the five year interval between 2012 and 2016, the frequency of conveyor chain link failure has had a 34% increment from 33 to 50. Therefore a study into the reasons behind the failure will go a long way towards either eliminating these failures or reducing the frequency at which failure occur. Failure of conveyor chains is not only a major problem for cement industrial sector but for other sectors which make use of conveyor chains. Historical data had shown that, the chain link is the major cause of failure for conveyor chain assembly [1]. As conveyor assembly failure results in huge losses for the user, it is of paramount importance to have a detailed analysis conducted into the cause(s) of failure.

From a theoretical viewpoint, the chain is a continuous flexible rack engaging the teeth on a pair of sprockets which is a form of gear whose teeth are shaped to mesh with a chain. Basically, the chain is a mechanical belt running over sprockets that can be used to transmit power or convey materials. Chain strips are machine elements that are subjected to extreme service conditions, such as high tensile loads, friction, and sometimes aggressive operating environment which includes presence of humidity, seawater and chemicals, among others. Apart from tensile overload fracture, double shear is also a common failure mechanism which occurs under lower applied loads [2]. As these chains operate under various forces, failure of chain assembly is a major problem.

The causes of these failures may include improper material selection and flaws in the manufacturing processes. From the data obtained from East African Portland Cement (EAPC), the chain links of the bucket elevator are the most vulnerable to failure compared to other machine components such as the shaft, bearings, buckets, sprocket and the electric motor.

The chain link is made up of an inner and an outer link which are press fitted to form a continuous chain. Fig. 1 shows the various components of the conveyor chain link that are assembled to form a continuous chain.

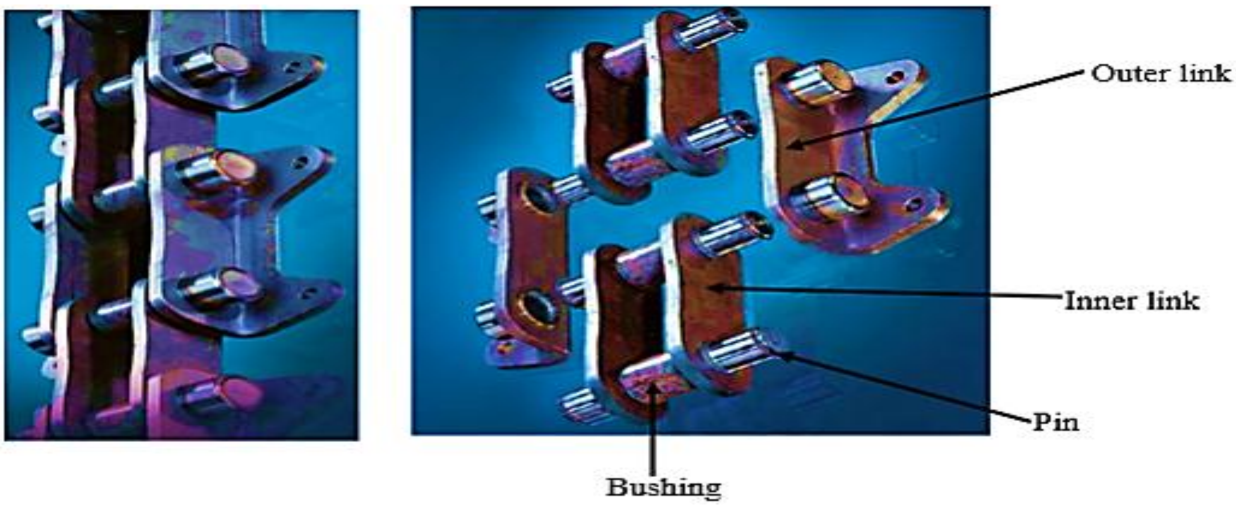

Figure 1: *Typical chain link assembly.*

Haris investigated the causes of failure of a chain system through characterization of the failed component [3]. The analysis revealed that the weld defects such as craters lead to crack propagation and a cyclic loading causes the fatigue failure.

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The fatigue failure occurred due to this inherited crack at the outer circumference of the weld within chain attachment and outer chain link plate. This type of defect can also be categorised as designing-in defect. Fatigue crack propagation was evident by progressive beach marks and the scanning electron microscopy (SEM) analysis revealed the types of microstructure that resulted at the heat affected zone (HAZ). Hardness testing by using Rockwell Tester found the different hardness profiles at the three areas, i.e., weld metal, base metal and heat affected zone. The maximum hardness values were found at the heat affected zone and the weld metal. Cracks generated at the outer circumference of the weld within chain attachment and outer chain links plate within the material led to fatigue failure. Haris proposed that the thickness of the outer link be increased but didn’t relate it to how this increase will impact on the weld strength or weld defects (craters) within the chain link.

Bošnjak et al. [4], carried out failure analysis on a Stacker Crawler Chain Link. The goal of the study was to diagnose the cause of chain link breakdown. Working stresses in the chain link were calculated by applying FEM. Experimental investigations were also carried out including; chemical composition analysis, tensile properties, impact toughness and macro and micro-hardness. Metallographic examinations were conducted additionally. Based on the results of the numerical-experimental analysis, it was concluded that chain link breakdown is predominantly caused by (a) substantial deviation of the mechanical properties of the material with respect to those prescribed by the standard and (b) the existence of macro and micro cracks in the material structure. It was therefore concluded that the failure of the chain link was caused by ‘manufacturing-in defects. The origination of the macro and micro cracks were not stated; whether they were inherited, whether they originated from grain boundary or inclusions and therefore the root cause of failure could not established.

Momcilovic et al. [5], investigated a failed bracket of a conveyor using Scanning Electron Microscopy analysis and established the presence of oxide on the crack surface. The authors observed that the contact zone between chain link and bracket is one of the most stressed zones and fracture always occurred in that zone. Based on their research, they concluded that the origin of cracks in chain brackets in this case was due to the production process, because the wrinkling of the material appeared during hot bending. The implications of the oxide found on the crack surface were not stated and also the relationship between the wrinkling of the material and the crack were not established.

Sujata et al. [6], in their study using visual examination found a shallow crack on the surface of the chain link. Under stereo-binocular microscope, the authors found that the fracture surface showed coarse crystalline features. The sample containing the crack was cut, mounted, metallographically prepared and observed under an optical microscope. Visual examination revealed a crack-like surface defect and the optical micrograph showed oxide entrapment in the material near the surface. In between the crack surfaces, the authors used Energy Dispersive X-Ray (EDX) analysis in SEM for investigation and found that the non-metallic inclusions were mainly iron oxide. The authors concluded that the conveyor chain links had failed due to presence of manufacturing-in defects. The defects were identified as forging laps or folds and can be summarized as inherent defects. The investigation also showed that, surface defects were present in the billet itself.

They then recommended that the billet be properly dressed and the surface defects be removed prior to the forging operations. The significance of the coarse crystalline features and the iron oxide inclusions were not stated in this paper.

Singh et al. [7], studied the failure of bridle chain used for hoisting in the mines. Laboratory examination proved that the defect is a mechanically induced one. Visual and stereo-binocular observations revealed surface defects in samples. It was observed that it was not safe to strain the chain beyond the elastic limit of the material. It was concluded that the cause of failure was as a result of inherited defects in the material and that the chain can fail mechanically by overloading, fatigue and wear. The type of inherited defects were not stated. The maximum load the investigated chain link can withstand and the maximum load conveyed by the conveyor chain link were not stated and therefore it cannot be concluded that overloading was the cause of failure.

Bosnjaka and Arsic [8], investigated the cause of the chain link breakdown on a hydraulic excavator. Its superstructure leans on three crawlers of the same length, width and the height. During the stackers travel from the erection site to the open pit mine, three crawler chain links fractured. The working stresses in the chain link were evaluated by finite element analysis (FEM). Experimental techniques were used to investigate the chemical composition, tensile properties, impact toughness, and macro and micro hardness. Based on the numerical and experimental analysis, the authors concluded that substantial deviation of the mechanical properties of the material with respect to those prescribed by the standard occurred and the presented failure of the chain link was caused by ‘manufacturing-in’ defects.

Bošnjak et al. [9], carried out a failure investigation of the bucket wheel excavator crawler chain link to diagnose the cause of the damage. In order to identify the reasons behind chain link failures, stress state calculations were performed as well as experimental investigations which included visual and metallographic examinations, chemical composition analysis and tests of mechanical properties. The sulphur content obtained from the chemical analysis of both samples was higher compared with specifications. This resulted in decreased impact toughness, particularly under impact conditions. The significant decrease of elongation compared with specified values confirmed the presumptions based on the results of the chemical composition. The obtained low values of elongation and contraction meant that the samples had very low resistance to crack initiation and crack propagation. Based on the results of the numerical and experimental analyses, it was concluded that the chain link breakdowns are caused by ‘manufacturing-in’ defects. The carbon content obtained from the chemical analysis was lower than that of the required standard but the paper never took into account this observation.

In summary, none of the papers could establish the root cause of the failure since the crack initiation could not be established. Also, original un-failed sample was not studied to establish any link between the failed and un-failed chain link samples.

METHODOLOGY

Visual examination, metallography and chemical analysis were employed in this study to analyse the cause of failure of the conveyor chain link.

Visual Examination

Visual examination was done on the factory site, un-fractured sample and fractured samples. With the aid of a stereo microscope, the fractured surface was magnified to see more clearly the fractured surfaces and surface defects for analysis. Special attention was paid to anomalies such as scratches, fractures, unusual marks and wear. This step was to examine fracture surfaces and to identify whether the fracture is ductile or brittle. Chevron marks always appear at a fractured surface as a result of the fracture process. Chevron marks are very helpful because they can point to the crack origin. Before the fractured samples was examined by mounting under the stereo microscope, it was first sectioned 12mm from the fractured surface as shown in Fig. 2 with a hacksaw (low speed cutter) so as not to alter the micro-structure.

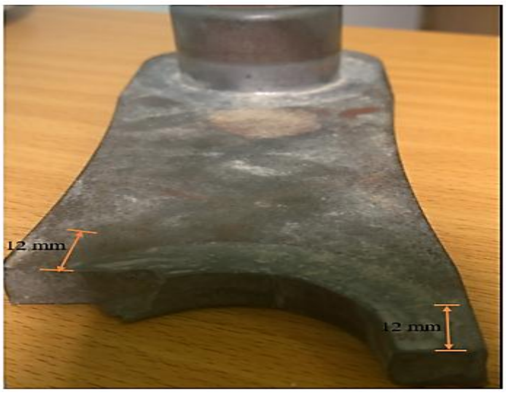

Figure 2: *Sectioning of failed sample.*

The sectioned samples were then mounted on a stereo microscope to observe the grains on the surface so as to deduce the type of fracture. Also the mechanism of failure was deduced by tracing the chevron mark on the surface as it shows the path for the failure.

Chemical Analysis

Chemical analysis of samples from the component provides information regarding any deviation from the standard specifications, compositional in homogeneities, impurities, inclusions, segregations. Five (5) samples were taken for chemical Analysis using mass spectrometer of model Maxx LMF06 at Numerical Machining Complex limited in Nairobi.

Metallography

After collecting all the information through fractography of the failed component, a section of the component was transversely to the fracture surface. The section was then polished and examined on a metallurgical microscope, both before and after etching. The microscope used was Optika of model B353 MET. Inclusions present in the material were observed on the as-polished surface. The polished specimen was then etched with suitable etchants to reveal the microstructure of the material. Abnormalities in the micro-structure that may have been responsible for the failure can be identified at this stage.

The following procedure was followed in polishing of the samples;

- The already sectioned samples (failed and un-failed) during visual examination were ground on four (4) silicon carbide papers of grade 220, 320, 400 and 600.
- After grinding was completed, the specimen was washed with water flushed with methanol and dried with a drier before polishing was done on a polishing machine.
- Polishing was done using 6 and 4 micron diamond paste. The diamond paste was put on the polishing cloth. Lapping fluid was put on the polishing cloth with the diamond paste.
- After polishing the sample with 4 micron diamond paste, it was then washed with water, flashed with methanol and then dried with a drier to obtain the final polished sample. The procedure was repeated for the other un-polished samples.

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RESULTS AND DISCUSSIONS

Visual Examination

The preliminary examination was done in two sections, namely; on the factory site and on the fractured surface for analysis.

Visual Examination on Factory Site

The preliminary examination done at the factory site revealed indentations on the chain links which is as a result of the sprocket impacting on the chain link as shown in Fig. 3. This is an indication that misalignment do exist in the bucket elevator system and must be eliminated. This impact force of the sprocket on the chain link aided in the progression of the cracks generated by the inclusions within the chain link. The impact force was one of the main sources of vibration and noise existing in the bucket elevator. It also resulted in the stretch and fatigue of the chain links.

The result of vibration is unsteady chain speeds which affect the engagement process as well as the impact levels. Accurately alignment of sprockets is very important to the life of both the chain links and sprockets as the life of a properly aligned sprocket can be maximized and in so doing also ensures that the bucket elevator operates at maximum efficiency. It was observed that the sprockets were not in alignment as there was an offset between the two shafts and the sprockets.

Due to this, the chain forces were not evenly distributed to each tooth of the sprockets, thereby increasing the tension in the chain. Accurate alignment of shafts and sprocket tooth faces provides a uniform distribution of load across the entire chain width and contributes substantially to maximum drive life and also reduces the wear and the damage of the sprockets and chain.

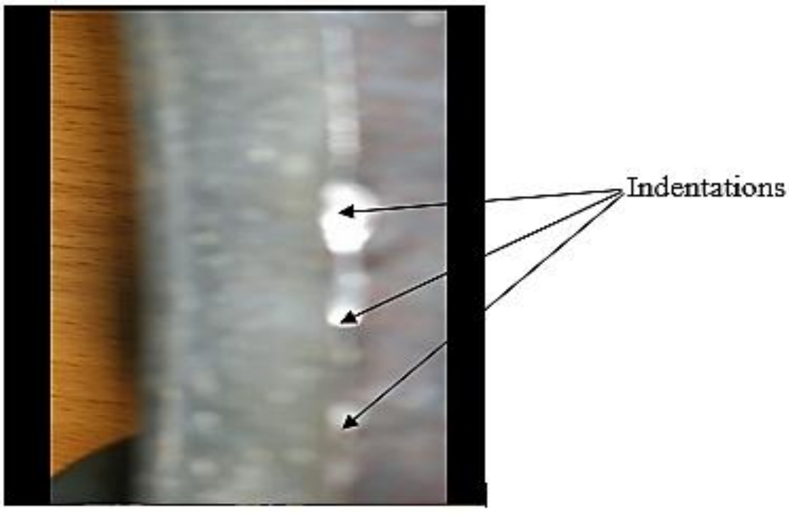


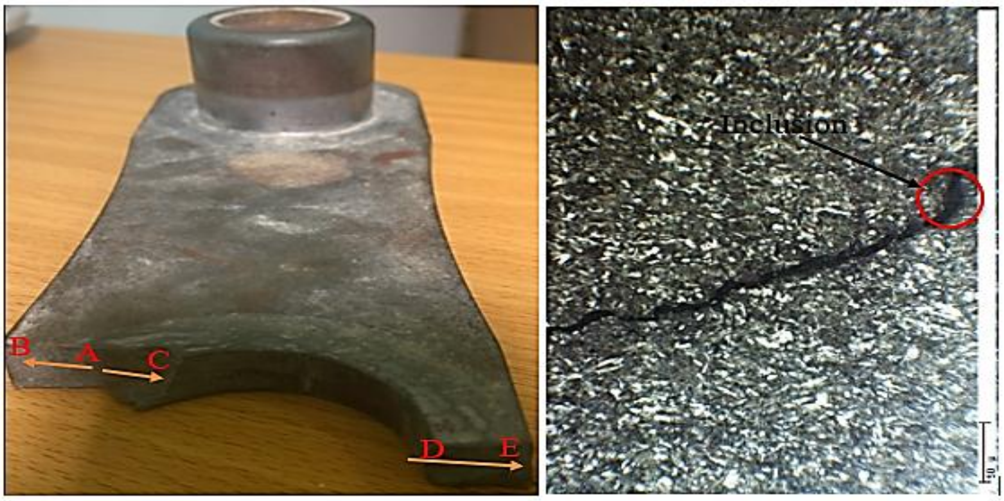
Figure 3: *Indentations on chain link.*

Visual Examination on Fractured Surface

Observing the fractured surface using stereo microscope revealed that the type of fracture was brittle fracture as smooth grains appeared on the fractured surface. Brittle fracture also occurs as a result of induced inclusions at grain boundaries [10]. Fig. 4 shows that the crack had initiated from an inclusion which points to the fact that the fracture is of brittle type. Another observation that emphasize that the fracture was of the brittle type was that the fractured surface for all the samples were without any necking.

Figure 4: *Failed chain links.*

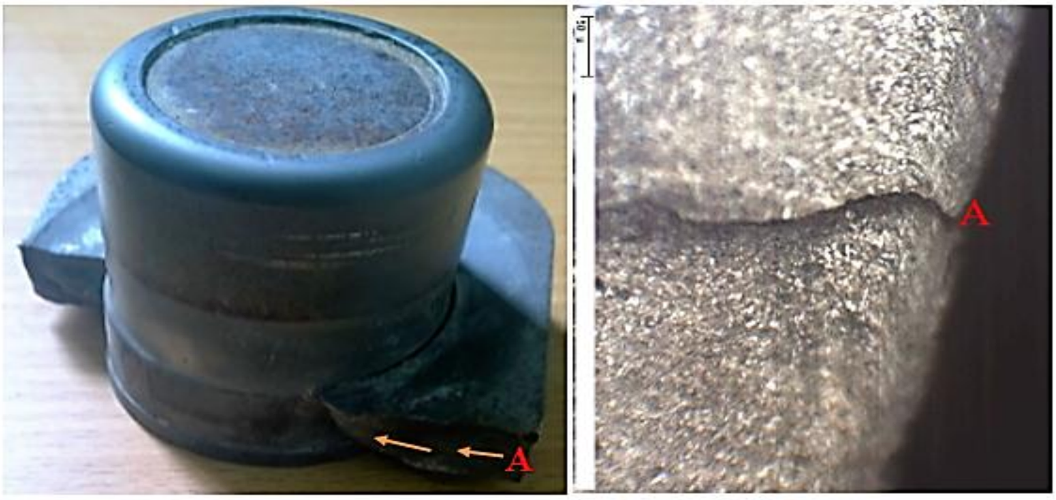
Fig. 5 shows that the crack had initiated from an inclusion which points to the fact that the fracture is of brittle type. Another observation that emphasize that the fracture was of the brittle type was that the fractured surface for all the samples were without any necking. Also, the mechanism of failure was obtained by tracing the chevron mark on the fractured surface. The chevron mark showed that the fracture initiated from the core of the fractured surface of the chain link and progressed outward until it snapped i.e., A → B → C → D → E as shown in the Plate 5.



(a) Crack initiation (b) Crack growth

Figure 5: *Fracture mechanism initiating from the core.*

Fig. 5 (a) shows that the crack began at point A and progressed gradually to the surface at point B. Since the chain link is under tensile loading and the crack had already been initiated at A and grown to B, it then progressed from C to D and finally fractured at E. The initiation and growth of the crack from A to B is as shown in Fig. 5 (b). The point of fracture initiation was dependent on where the inclusion which was the cause of failure was located; whether at the surface or the core. Fig. 6 shows a sample where the crack had initiated from near the surface and progressed until eventual fracture occurred. Fig. 6 (a) shows the crack initiation whereas, Fig. 6 (b) shows the crack growth. The point at which the crack initiated was therefore dependent on the location of the inclusion from which the crack had initiated from.



(a) Crack initiation (b) Crack growth

Figure 7: *Mechanism of failure initiating from boundary.*

Chemical Analysis

The chemical analysis was done on five different failed chain link samples and yielded the following results as shown in Table 2. From the chemical analysis, it was deduced that the grade of steel was EN10293

Table 2: *Chemical analysis results.*

Sample	Element	C	Si	S	P	Mn	Cr	Mo
1	Content (%)	0.131	0.345	0.0002	0.000510	1.49	1.47	0.174
2	Content (%)	0.133	0.361	0.0003	0.000581	1.51	1.50	0.183
3	Content (%)	0.135	0.372	0.00042	0.000652	1.51	1.54	0,180
4	Content (%)	0.202	0.429	0.00015	0.000552	1.48	1.60	0.179
5	Content (%)	0.129	0.331	0.00035	0.000592	1.49	1.61	0.175
	Standard (%)	0.27-0.34	Max 0.6	Max 0.02	Max 0.025	Max 0.5-1.7	Max 1.3-1.7	Max 0.15-0.5

The two elements that are detrimental to steel are Sulphur and phosphorus. Sulphur promotes internal segregation in the steel matrix. Both Sulphur and phosphorus act to reduce the ductility and weldability of the material. They must therefore be held to less than 0.020 max. for Sulphur and 0.025 max. for phosphorus. From the chemical analysis they are all within range. Carbon plays an important role in the hardness and ductility of steels. The higher the carbon content the harder the steel but the ductility reduces and vice versa. For this reason the carbon content for chain link is limited to 0.27- 0.34 [11].

From the chemical analysis, the carbon content for the five samples were all below the required standard of between 0.27-0.34 and therefore do not meet the requirements according to the British standards for steel manufacturing. Lower carbon content can also aid in fatigue fracture as a result of lower hardness. The carbon content is low but the manganese and chromium content are high. Manganese and chromium addition to steel increases the strength and hardness of the steel which compensate for the lower carbon content as stated earlier.

The lower carbon content therefore helps in improving the ductility whilst high manganese and chromium content improves the strength and hardness of the steel. Therefore, the lower carbon content is compensated for by higher manganese and chromium content and cannot be the root cause of failure but a contributing

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factor to the cause of failure. This is because the lower carbon content means that more oxygen is required in the reduction of the carbon content which in turn will increase the oxygen concentration level in the steel matrix. More de-oxidant will therefore be required to de-oxidize the steel to the standard oxygen levels required for steel (2-4 ppm). This increases the probability of more amount of dissolved inclusions to be formed.

The higher chromium content further causes the steel to be resistant to corrosion and high temperature strength as the bucket elevator conveyor chain operates between temperatures of 70 to 100°C.
Molybdenum meanwhile increases the tensile strength as well as helps in the formation of fine grains as fine grains are more desired than coarse grains in steel manufacturing because they give better strength. From the microstructure, it was observed that the grains were fine and this was due to the addition of molybdenum.
Silicon serves the purpose of deoxidization as it has higher affinity for oxygen and therefore reacts readily with oxygen and also improves the castability of the steel by increasing it fluidity.

It was therefore concluded that the lower carbon content might not be the root cause but rather a contributing factor in the failure of the conveyor chain link

Metallographic Analysis
The microstructural analysis was done in two parts, namely; on the failed and un-failed chain link samples. Different samples of both failed and un-failed samples were examined.

Microstructural Analysis on Un-failed Samples
The polished failed samples were etched in an etchant made of 98% methanol and 2% nitric acid (Nital) to reveal the micro-structure. The micro-structure observed under an optical microscope with magnification 500x is as shown in Fig. 8 and 9.

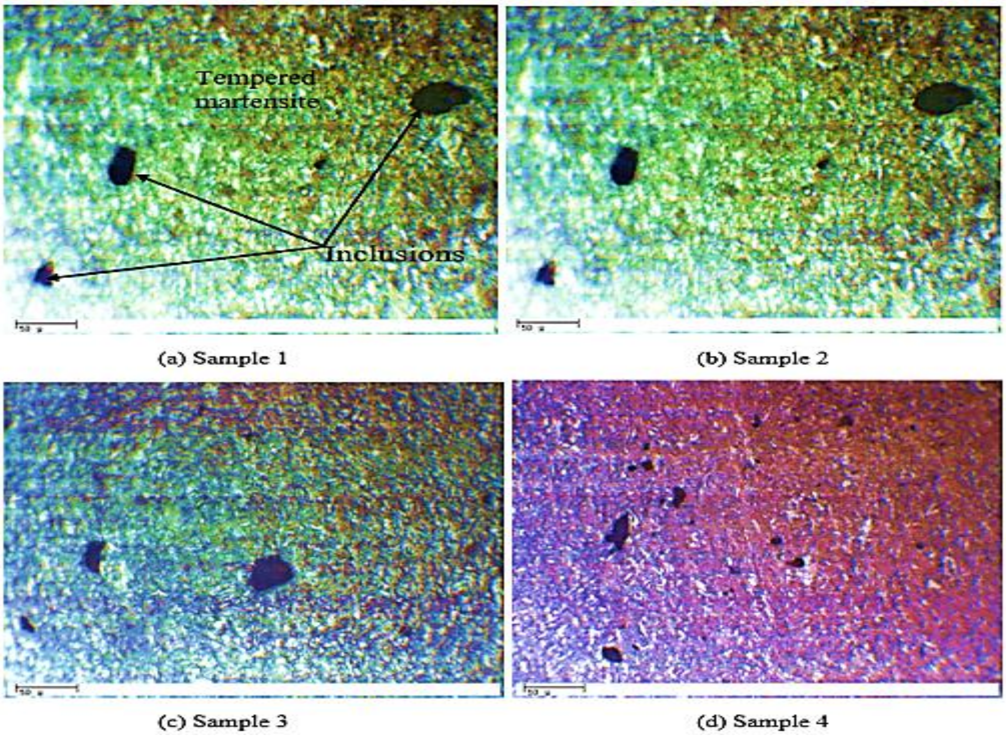

Figure 8: *Micro-structure for Un-failed chain link sample showing inclusions for samples 1 to 4.*

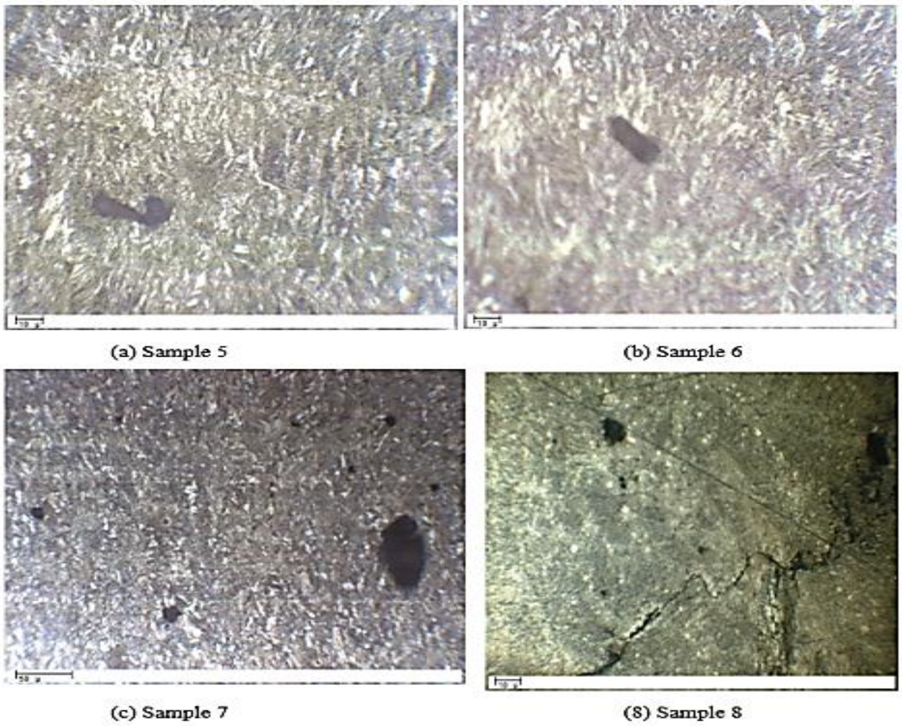

Figure 9: *Microstructure for Un-failed chain link sample showing inclusions for samples 5 to 8.*

The micro structure of the un-failed chain links is that of a tempered martensite. Martensite in its quenched state is very hard and brittle and because of this brittleness, martensitic steels are usually tempered to restore some ductility and increase toughness [12]. The samples do share the same microstructure but the size and distribution of the inclusions differ as shown in Fig. 8 and 9. Inclusions are known to have low formability and during loading they produce cracks in the steel. Also inclusions produce cracks during heating because of different co-efficient of thermal expansion between steel and inclusion which results in higher stress development and subsequent cracking. Although, the presence of inclusions can never be entirely avoided, the quantity, size, shape, distribution and composition can be modified to achieve better mechanical properties [13]. These cracks then propagated during loading leading to the eventual fracture of the material.

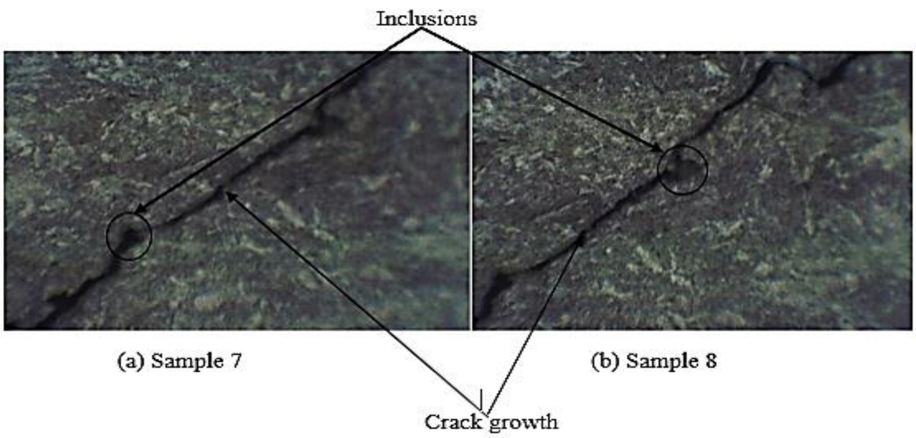

Figure 10: *Cracks within material.*

The cracks on the various samples studied were observed to have initiated from an inclusion as shown in the Fig. 8, 9 and 11.

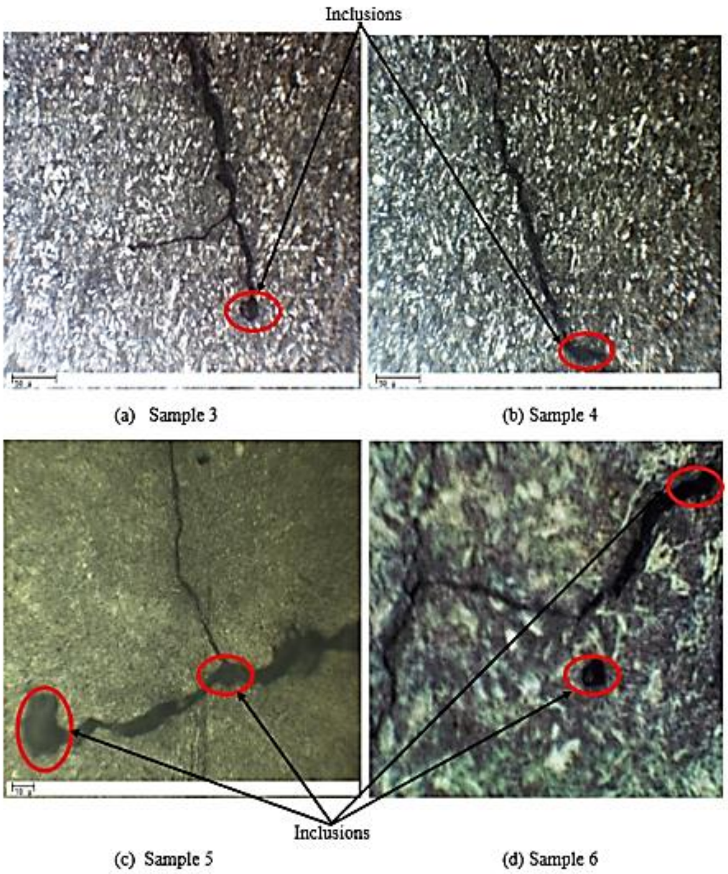

Figure 11: *Cracks initiation from inclusions from failed samples.*

For other samples studied the failure was observed to have initiated from the boundary as shown in Fig. 12 as a result of the inclusion located at the boundary. The point at which the crack initiated was therefore dependent on the location of the inclusion from which the crack is initiation from.

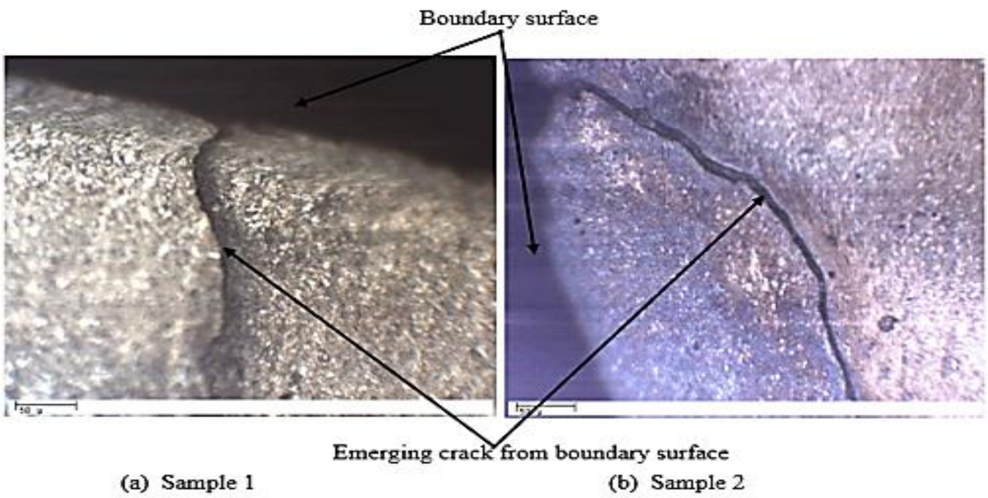

Figure 12: *Cracks initiation from boundary.*

Brittle fracture was therefore the root cause of failure of the conveyor chain link induced by inclusions as shown in Fig. 9, 10 and 11. This is further emphasized by the fact that there was no necking as well as the grain on the fractured surface being smooth.

Most of the inclusions in steel are the product of the de-oxidation process. The aim of de-oxidation or "killing" is to reduce the dissolved oxygen content of the steel. As the steel solidifies, oxygen dissolved in the liquid cannot be accommodated by the solid crystal structure; it therefore reacts with dissolved carbon forming CO gas which is trapped in the casting as porosity or pinholes. The addition of deoxidizers to molten steel reduces the dissolved oxygen in the system through the formation of liquid or solid oxide phases. When the steel starts to cool, there is a corresponding decrease in oxygen solubility and inclusions precipitate to satisfy the new and constantly changing equilibrium conditions. The inclusions which precipitate early in the cooling process have a greater opportunity to escape through flotation. However, as the metal solidifies and dendrites continue to grow larger, the inclusions which precipitated late during solidification become entrapped, and appear as small non - metallic phases in the finished product [14].

Casting operation and steel quality are greatly affected by both composition and the quantity of inclusions present in steel. Problems of nozzle clogging during casting are often related to micro inclusions that are solid at steel making temperatures promoting nozzle blockage [15, 16]. Since inclusions cannot be eliminated completely from steels, it is imperative to modify them with calcium in terms of chemical composition to minimize their harmful effect. Calcium (modifier) addition is therefore the solution to eliminating these inclusions by chemically reacting with them to form calcium aluminate. The calcium aluminate floats at a faster rate and produces cleaner liquid steel [17]. Calcium aluminate improves machinability, toughness and surface quality rather than being a crack initiation point [15].

Stress-concentration factor is normally introduced to relate the actual maximum stress at a discontinuity (marks, holes, notches, grooves, threads etc.) to the nominal stress. Discontinuities or stress raisers alters the stress distribution in the neighborhood of the stress raiser and therefore the need to introduce stress concentration factors.

From the design point of view, the problems of inclusions can be solved by introducing stress concentration factors for inclusions as these inclusions tend to raise the stresses in the region where these inclusions are located. The factors which are responsible for change in stress concentration are; change in modulus of elasticity of the inclusion and the steel matrix, changes in the type of bonding at the inclusion metallic interface, creep effect and dislocation processes near the inclusion.

CONCLUSION

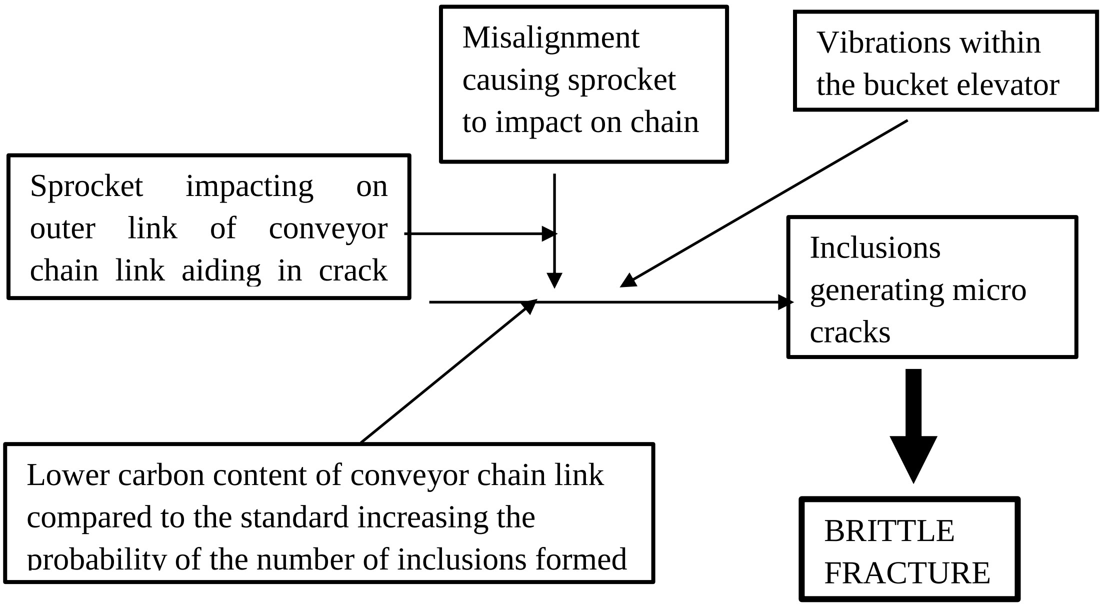

Figure 13: *Fish bone diagram for the causes of failure.*

In conclusion, the root cause of failure was deduced to be brittle fracture as there was no necking at the fractured surface as well as the grains on the fractured surface being smooth. Fig. 13 shows a summary of causes of failure. The point of initiation of the fracture was found to be from inclusions within the chain link and therefore were source of crack initiation. These inclusions generated micro cracks within the material which progressed during loading. The impact forces which were generated as a result of the sprocket teeth impacting on the chain links also aided in the progression of the cracks and therefore a contributing factor (secondary cause). The lower carbon content was also a contributing factor as the probability of increasing the number of inclusions formed during de-oxidation is increased by increased amount of dissolved oxygen used for reducing the carbon content. These inclusions were either located at the surface or the core and therefore the fracture had initiated either at the surface or the core depending on the location of the inclusions. It was recommended that in order to eliminate the problems associated with these inclusions from the design point of view, a stress concentration factor for inclusions must be introduced at the design stage as inclusions cannot be eliminated completely from the steel matrix.

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