# Reliability Modelling Through Deterioration Prone Components

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## Abstract

Deterioration prone or wear components identification and technical analysis of functional loss characteristics entail a detailed analysis of the failure characteristics of components through the understanding of their failure modes and the technical characteristics of their failure patterns. Maintenance actions are then prescribed to prevent functional failures or to proactively repair the components in a bid to prevent failure(s) in the operational field. The determination of ensuing maintenance actions focusses on those actions that are vital to monitor and eradicate unreliable conditions on the components under consideration. Deterioration prone machinery components afford maintenance practitioners with the openings to improve physical assets reliability, and this study was embarked on to explore reliability amelioration prospects that are availed through identified components deterioration.

## Keywords

Deterioration, wear-components, functional-loss, reliability

## 1. Introduction

Installations such as petrochemical plants have physical assets that are multifaceted and operate under arduous circumstances, and their deterioration over time is imminent, and this is brought about due to age, wearing, corrosion/erosion, fatigue and other factors (Hameed and Khan, 2014: 18). There are many asset reliability improvement opportunities that can be capitalized on the deterioration prone or wear components of physical assets

and technical processes need to be developed to harness such opportunities. The detailed exploration of the components' functional failure characteristics render a path of unblemished appreciation of the failure modes and the technical aspects of the patterns they trail during the failure process. Amplifications of the severity of failures can raise the dependability of forecasting by means of the likes of Bayesian statistical techniques (Sørensen, 2009:493). Strategic maintenance arrangements are then apportioned as an anecdote to suppress failures or to proactively reconstitute the asset part to elongate its reliability lifespan. The fortitude of strategic maintenance initiatives emphasize on the engagements that are momentous to screen and exterminate un-reliable settings on the asset part.

## 2. Common Component Deterioration patterns

Generally, the deterioration contraptions that incorporate fatigue, corrosion, wear and erosion are allied with noteworthy ambiguity (Sørensen, 2009:493). Abrasive wear occurs in components such as couplings that are accommodative of misalignment brought by sliding motion (Pakale and Tuljapure, 2015:414). This is further aggravated by wear particles mixing with the remnant lubricant, generating an abrasive paste, of which this paste accelerates the wear rate if allowed to exist in a coupling assembly (Pakale and Tuljapure, 2015:414).
Fatigue failure is one common type of deterioration that occurs in physical components that are subjected to cyclic loading, and its propagation is gradual, and can cause component failure without any sort of warning, when the stresses in the component surpass the endurance limit (Pakale and Tuljapure, 2015:414). Figure 1 below illustrates coupling bolts that failed due to stress fatigue.

Figure1: Coupling bolts that failed due to stress fatigue (Pakale and Tuljapure, 2015:414).

Erosion is considered inevitable within the pipelines conveying bulk solids by means of hydraulic/pneumatic conveyance systems, and the cumulative erosive wear hinges on a multitude of aspects such as material hardness, dimensions and outline of the solid particles, the solids concentration, conveyance speed and angle of impact of solid particles on the containing surface (Rawat, et al., 2017:114). The figure 2 below illustrates the rate of material wear changes due to increases of solids concentration.

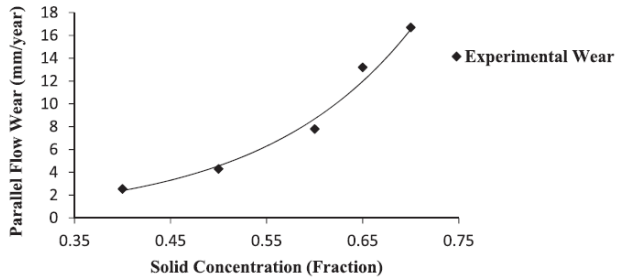


Figure 2: Changes of Erosion Wear as Solids Concentration Increases (Rawat, et al., 2017:120).

Experimental explorations have shown that erosion-wear has relatively sturdier functional dependency on the concentration levels of solids rather than the velocity of flow of the particles when high-concentration fly-ash slurry was analyzed for practically parallel-flow (Rawat, et al., 2017:120).

There is also another type of wear which is regarded as adhesive wear and in this wear mode, a transfer of material occurs from a surface and get smeared to another surface with this process being initiated by frictional heating, and the deterioration that ensues is regarded as "galling" or "scuffing" (Trivedi, et al., 2016:363). Adhesive-wear is triggered by the atomic interaction between metal surfaces functioning in a boundary lubrication zone where the specific film thickness is less than unity ($\lambda < 1$) (Trivedi, et al., 2016:363). The figure below shows the phenomenon of adhesive wear.

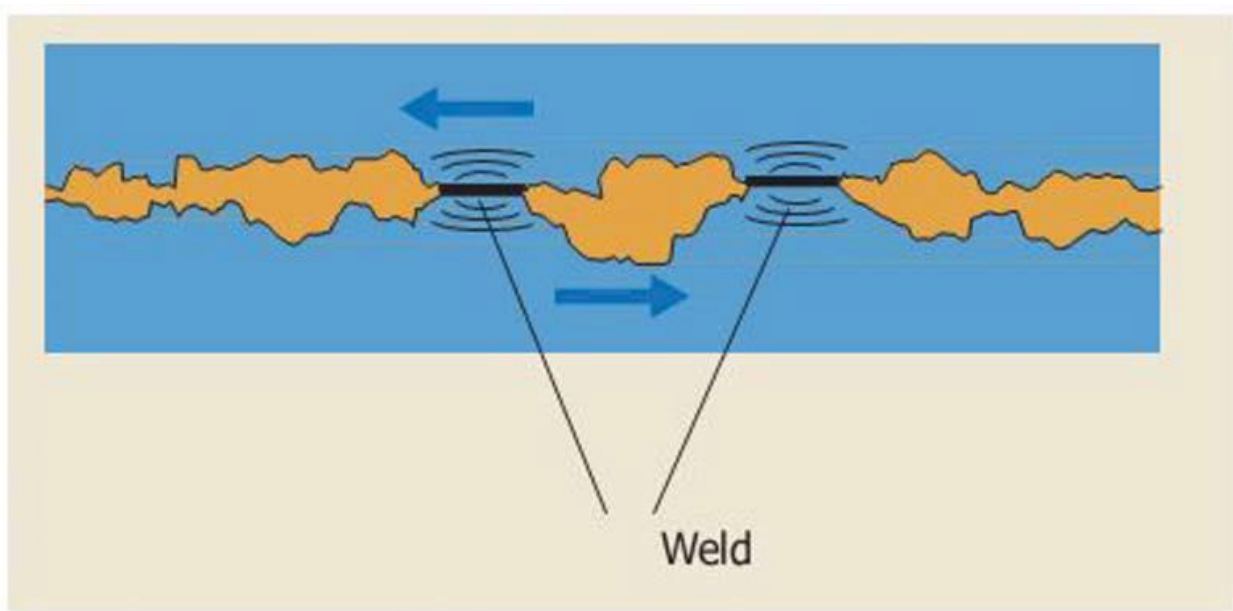


Figure 3: Phenomenon of adhesive-wear (Trivedi, et al., 2016:364).

Corrosion is a form of deterioration of a metallic material and its properties as a result of chemical/electrochemical reactions with the adjoining environs, and the worst consequence is a component or asset functional loss (Craig, 2006:12). In many applications, the deterioration of materials is attributable to the combined effect of erosion and corrosion, and this culminates in erosion-corrosion (Tian et al., 2009:2047). Erosion–corrosion is reckoned as the one utmost austere type of material deterioration that occurs in hydraulic system assemblies (Giourntas et al., 2015:1051). Erosion–corrosion as a material deterioration phenomenon occurs in hydraulic systems that handle abrasive slurry fluids, and this has resulted in numerous industrial entities attempting to alleviate this reliability challenge through modifications of the designs of physical assets and/or by opting for added erosion–corrosion resilient materials (Giourntas et al. (2015:1051), Rawat, et al. (2017:124)). The erosion–corrosion mechanism entails

unadulterated mechanical deterioration (E), untainted electrochemical degradation (C) and additionally, the collaborative effect of both processes, which is broadly called synergy (S), of which these factors can have an equational format depicted below.

$$TML = E + C + S \quad (1)$$

Where TML is the total mass loss (Giourntas et al., 2015:1051). A typical erosion-corrosion time based profile is illustrated in the figure below.

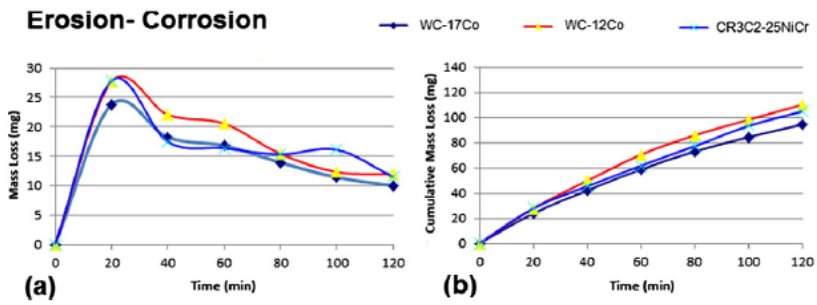


Figure 4: Typical wear rate for coating materials under testing (Lima et al., 2015:132).

Erosive wear is a plastic deformation process of material occurring during the time the collision surpasses the elastic limit, and further continuous impeachments culminate in the yield-strength increasing due to the plastically distorted surface hardening, and as the surface develops harder and more brittle, it cannot endure to distort plastically, and the stratum gets to a point when it starts to chip (Lima et al., 2015:127). This scenario is framed mathematically by the following equation:

$$W_D = \frac{1/2M\left[V \sin \propto - KT^2\right]}{\varepsilon} \quad (2).$$

where $W_D$ denotes the erosive-wear, M denotes the weight of the material, α is the incidence-angle of the abrasive constituent part, KT is a coefficient that incorporates the capability of the material(s) to distort plastically and ε is the energy necessary to get rid of wear particles (Lima et al., 2015:127).

The erosive-wear of any material may be projected through an equation as:

$$E = \propto . V_0^{2.4} . d^{2/3} . \rho^{1.2} . K_{Ic}^{-4.3} . H^{0.11} \quad (3)$$

where E denotes the erosive-rate, α is the incidence-angle of the abrasive constituent part, d being the diametrical dimension of the abrasive constituent part, ρ denotes the plastic-flow, $K_{IC}$ denotes the fracture–toughness and H being the material hardness (Lima et al., 2015:127). Various studies have revealed that different materials' erosive-wear resistance change due to the increased material hardness promulgated by plastic deformation (Lima et al., 2015:127). A slight variant of erosion-corrosion is termed tribo-corrosion, which is a material deterioration phenomenon instigated by the synergistic consequence of corrosion and wear simultaneously impacting on a surface, and it is prevalent in various engineering situations (Tekin and Malayoglu, 2010:563). Below is a display of images of erosion-corroded surfaces.

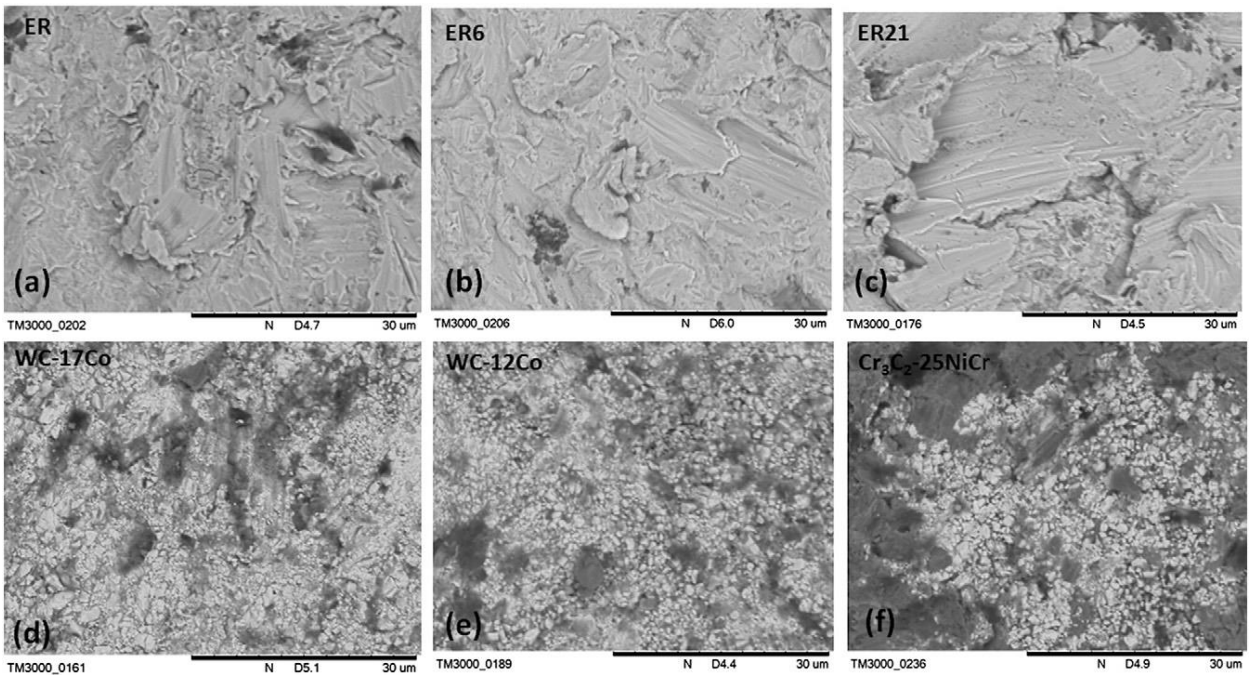


Figure 5: Images of test samples of erosion corroded surfaces in metallic coatings (Lima et al., 2015:132).

The different deterioration modes are summarized in the figure below. The other deterioration modes that are not covered in detail in this research are included in the summarized diagram below.

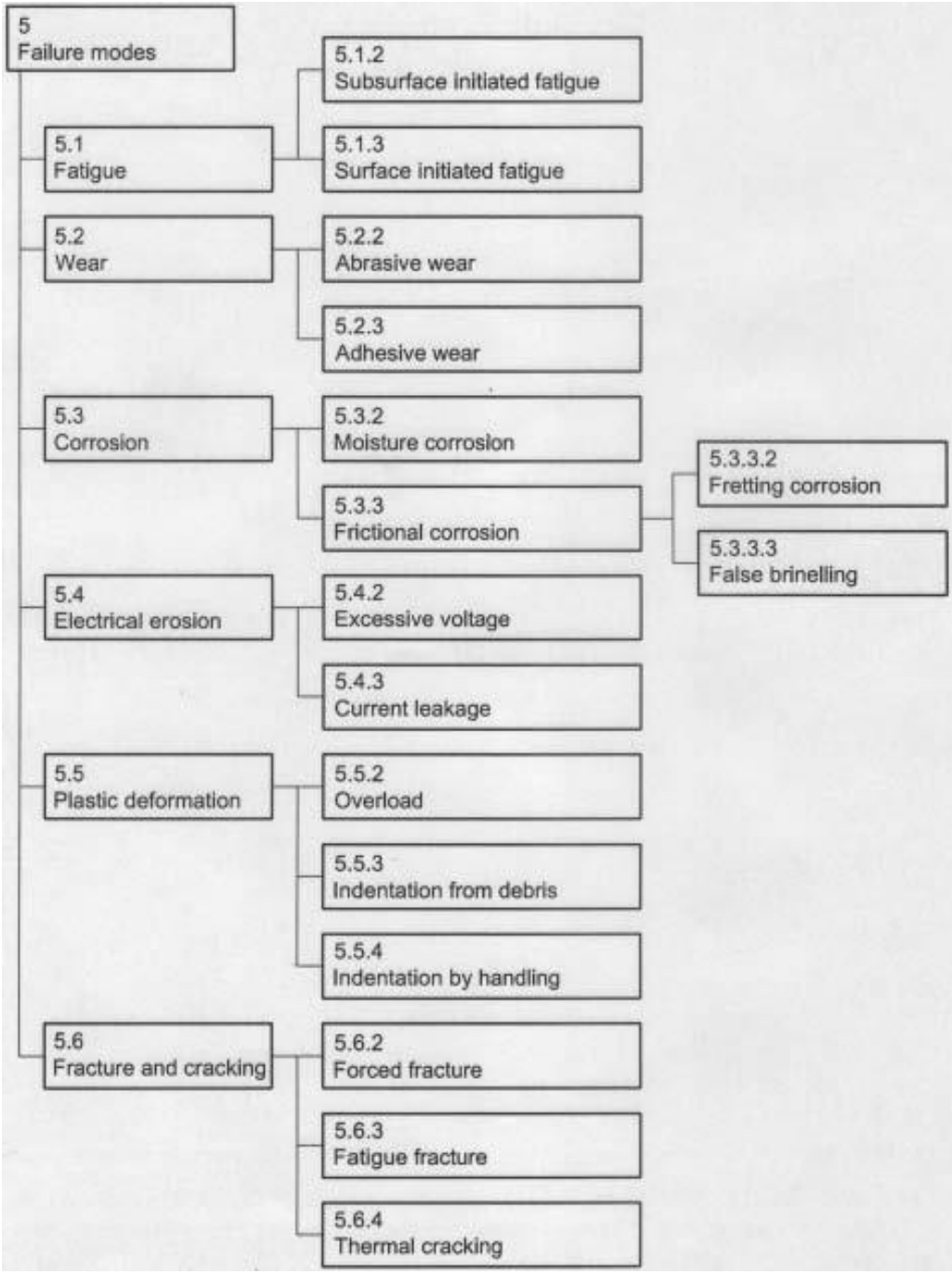


Figure 6: Cataloguing of component deterioration modes (Trivedi, et al., 2016:364).

## 3 . Formulating Reliability Models around Deterioration Patterns

Concerning various deterioration prone mechanisms such as wind turbines, the bath-tub model may be applied to demonstrate the advancement of the failure trend during the operational lifespan (Sørensen, 2009:497). The early stages are marked with expectations of high failure rates due to the infant mortality/burn-in defects, which can be followed by a phase of normal/ interval based defect rates, and this is when the corrective maintenance strategy can be deployed (Sørensen, 2009:497). Towards the expiration of the lifespan of the asset, the failure rate may be

expected to increase to higher levels, and this will call for the deployment of the preventative maintenance (Sørensen, 2009:497). In the event that the failure rate increases moderately and the deterioration could be identified before the functional failure, then this calls for the deployment predictive and risk-based maintenance strategies (Sørensen, 2009:498). The figure below demonstrates the bath-tub curve for lifespan failure rates changes.

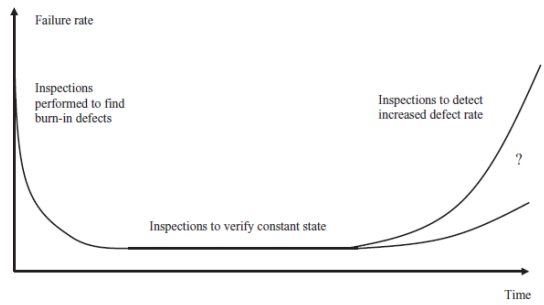


Figure 7: The bath-tub failure curve (Sørensen, 2009:498)

The inspection regimes are developed after considering the reliability risks posed at each stage of the lifetime of the asset and the typical inspection activities and component deterioration checks are discussed below. For instance, a gearbox can have prescribed (i) visual inspections through the inspection covers to confirm the magnitude of wear;
(ii) oil analysis can be done intermittently to indicate the magnitude of wear of internal components;
(iii) vibration response monitoring can be used to signal changes of mechanical components profiles (Sørensen, 2009:498).
But these evaluation approaches render indirect evidence on the deterioration status of the asset or component, as the deterioration status is not measured directly and the measures will possess diverse dependability with regards to the information pertaining to the deterioration state, and a reliability modelling that takes cognizance of the actual deterioration state is desirable (Sørensen, 2009:498).
There is need to develop reliability models that have the following traits:
• deterministic reliability modelling for deterioration buildup as a function of time.

The figure below shows an example of deterioration/damage accumulation over time.

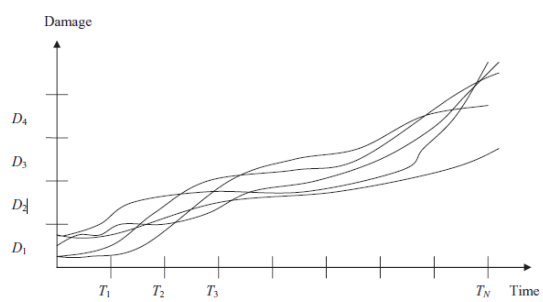


Figure 8: A linear model for deterioration/damage accumulation (Sørensen, 2009:500).

• stochastic reliability modelling for uncertain parameters in the deterioration buildup model that renders a provision that a probabilistic model for the deterioration buildup can be attained and computed
• stochastic modelling for the uncertainty or reliability of every inspection methodology
• decision modelling for repair or maintenance actions pursuant to the inspection or condition monitoring results
• cost modelling in relation to inspections, maintenance actions, repair activities and possible failures inclusive of operational losses (Sørensen, 2009:498).

Some failure trends can be branded to follow an exponential deterioration or damage pattern with an accelerated deterioration rate towards the end, and in such circumstances, the inspection intermissions ought to be compressed to shorter intervals causing significant inspection costs, but stabilized by minimal projected failure costs, or

alternatively, a design-out maintenance strategy is pursued (Sørensen, 2009:502). An exponential damage or deterioration trend is shown in the figure below.

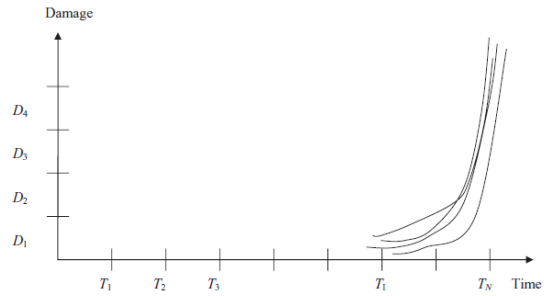


Figure 9: Deterioration/damage accumulation following an exponetial trend (Sørensen, 2009:502).

## 4. Maintenance Techniques to counteract deterioration and uphold asset Reliability

When the consequences of a failure due to deterioration are minimal, then the least extent of maintenance activities can be afforded by a business, but when the impact of the failure is magnificent, the deterioration of components and systems might cause unintended plant shutdowns, operational losses, and in some instances serious accidents and environmental impacts (Hameed and Khan, 2014: 18). As a means to minimize the losses, the deterioration rates associated with time and operations are tamed at minimal levels, and implementation of diverse maintenance strategies by which to guarantee the safety, reliability and availability of the production systems is pursued, so that they might endure to function dependably (Hameed and Khan, 2014: 18). Reliability is the crucial factor for any manufacturing operation as any physical asset failure may cause severe safety, financial or environmental consequences (Hameed and Khan, 2014: 18).
When the system deterioration can be modelled, it is feasible to forecast the failure intervals, and the maintenance activities may be planned on the basis of the service lifetime and the projected failure intervals (Hameed and Khan, 2014: 19).

The failure of a component or a physical asset is complementary to the reliability and is depicted mathematically as:
Rsys(t) + Fsys(t) = 1 (4)
Fsys(t) = 1 – Rsys(t) (5)
(Hameed and Khan, 2014: 21)

System failures can be sculpted using various techniques such as exponential, Weibull, normal or log-normal probability distributions, and Weibull distributions are widely applied in reliability evaluations due to the model's intrinsic elasticity and ability to mimic the performance of other statistical distributions, such as normal (for $\beta = 3.4$) and exponential (for $\beta = 1$) distributions.
The Weibull model with the parameters $\beta$ and $\theta$ defines the time dependent reliability of a component as:

$$R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}}$$

$$\lambda(t) = \left(\frac{\beta}{\theta}\right)\left(\frac{t}{\theta}\right)^{\beta-1} \qquad (6,7)$$

(Hameed and Khan, 2014: 22).

Within the field of reliability engineering, component failures are commonly categorized in three ways: (1) infant mortality failures; (2) failures with haphazard on-set times; and (3) end of life or 'wear-out' failures, and when the time distribution of failures of a sample of components is analyzed relative to a Weibull distribution, these

functional loss categories might be allied with form parameters β with values <1, ~1, and 1> respectively (Hall and Strutt 2003:233).

Infant mortality failures are regularly ascribed to inadequate design or improper material selection, or difficulties linked to manufacturing or assembling practices (Hall and Strutt 2003:233). When the accelerated deterioration is attributed to the material selection, the likes of Ni-based super alloys are broadly utilized in the industrial setup due to their great corrosion-resistance, mechanical strength and ability to preserve hardness at higher temperatures, and the alloys can function effectively at the high temperatures and at the same time being subjected to corrosion or wear during their service lifespan (Tekin and Malayoglu, 2010:564). Titanium based alloys likewise unveil outstanding corrosion resistance and are bio-compatible, rendering them appropriate for prosthetic uses like orthopedic transplants (Jaffery and Mativenga, 2012:479). Advanced materials and lubricants are being developed to meet the fatigue and corrosion resistance properties without deteriorating even in adhesive wear circumstances, and this is a significant challenge in materials engineering (Trivedi, et al., 2016:363). Impending materials for the likes of futuristic gas-turbine engines ought to incorporate high-performance characteristics, lubricants, and additives that can tolerate harsh operating environments like corrosion and high temperature, because at these elevated operational settings, it is projected that specific film thickness of lubricating materials will fall below unity, $\lambda < 1$, thus permitting surface to surface contact (Trivedi, et al., 2016:364). Various industrial applications call for materials with exceptional resilience to corrosion and wear, and this reason has driven the industry to use high-chromium white cast irons in areas of harsh abrasion and erosion environments (Tian et al., 2009:2039). Austenitic stainless-steels are broadly used in various industries as they possess exceptional corrosion-resistance, mechanical strength and durability (Zhao et al., 2015:464). Generally stainless steel can be brutally corroded by the likes of hot dilute sulfuric-acid, but the alloying of stainless steel with the platinum group materials greatly enhances its corrosion resistance due to the increased passivation effect by the noble elements (Li et al., 2015:200). Alternatively, the alteration of surfaces, which entail modifying only the surface coatings of a material, is currently trending as significant with the objectivity being to enrich the corrosion-resistance of various types of materials, and this is broadly applied to mild steel or other high carbon steels due to their ease fabrication and mechanical properties (Popoola et al., 2016: 448). Zinc or zinc-alloy coating is generally one of the high preferences when it comes to the need to coat iron and steel components when fortification from corrosion is the primary aim, and the techniques used for coating include electro-depositing by pulse current (Fayomi et al., 2015:328).

The various other techniques or measures that can be applied to improve the reliability of physical assets are listed below.

**To counteract corrosion:**
• Selection of materials with intrinsic corrosion- resistance in projected operational settings.
• Apply barrier coatings to corrosion - organic /metallic.
• Spread over surface treatments to produce even oxide layer on exterior of metals.
• Utilize vapor-phase inhibitors to disengage corrosive atmosphere in closed systems such as boilers
• Installation of sacrificial anodes or cathodic protection
• Implementation of mundane maintenance schedules to rinse material surfaces of any corrosive media
• Supplementing with alloy elements to metallic materials

**To counteract Erosion**:
• Prevent turbulence in fluid-flow.
• Addition of deflector plates when the flow impinges on walls.
• Enhance surface hardness through treatment or hard-coating

**To counteract stress/fatigue:**
• Design review of structural components to lessen stresses
(Craig, 2006:17)

## 4. Case Study – Maintenance Programme Development around Wear Components

A manufacturing establishment within the Johannesburg's East Rand area did an analysis of the functional loss of their physical assets, and identified the dominant failure modes and the results of their analysis was tabulated as per the graph below.

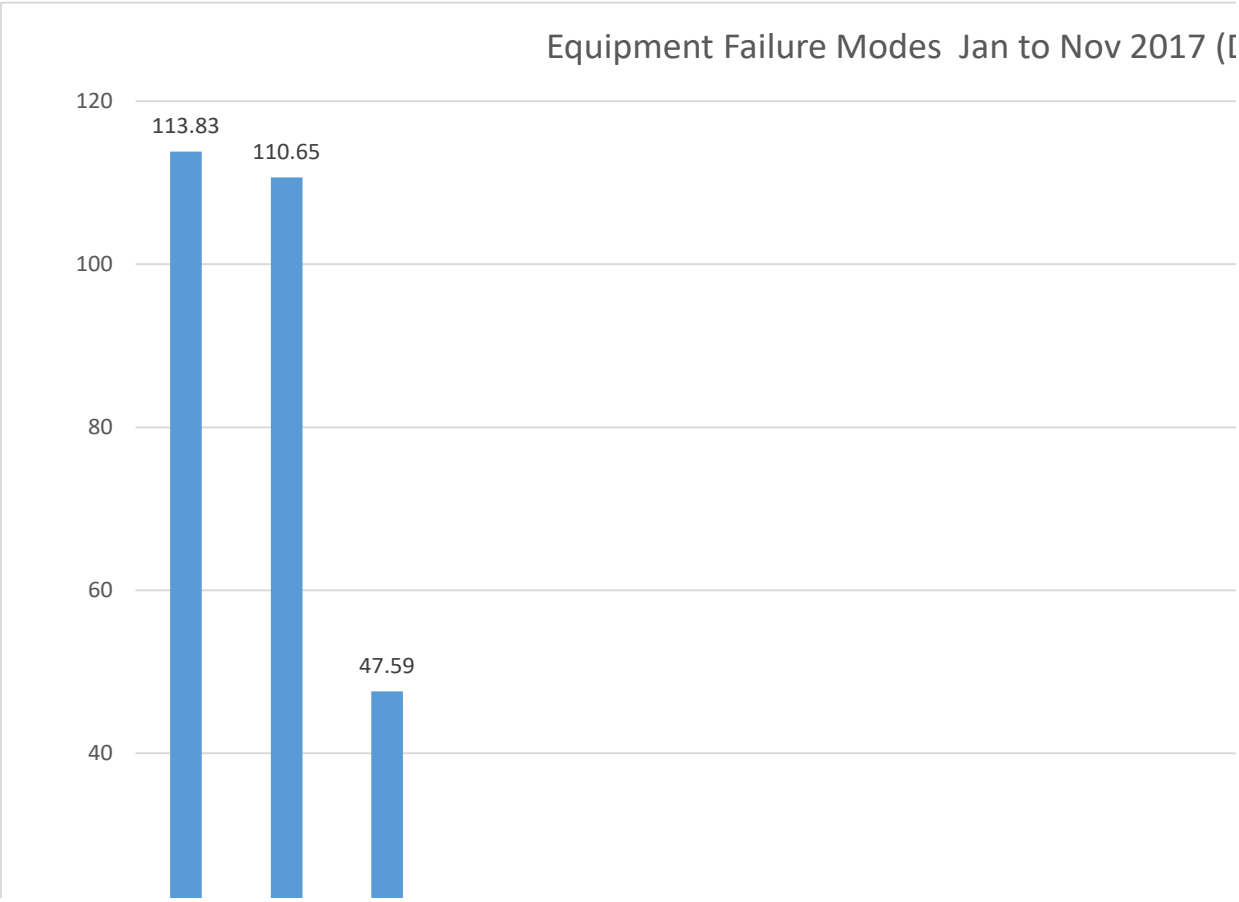


Figure 10: Processing plant equipment failure modes (Muganyi, 2017)

The analysis revealed that the two most prevalent failure modes were the broken/missing component and the worn component failures.

According to the analysis done during the review period (11 months), the total downtime for the plant was found to be:

Total Downtime (T) = 317 hours

The percentage contribution of worn components and broken/missing components was found to be:

$T_{(worn/missing)} = (113.83 + 110.65)/317$

$= \mathbf{70.8\%}$

The reason why the two categories were combined is because some components were broken as a result of deterioration (worn components). And basing on this assumption, a project was undertaken to address the failures pertaining to deterioration.

Two types of deterioration were identified, and these were natural and forced deterioration. The definitions afforded to the two types of deterioration are given below.

**Natural deterioration** – Normal wear-out that occurs in spite of proper use and maintenance

**Forced/Accelerated deterioration** – caused by human factors and occurs over a much shorter period. Forced relates to assets abuse or operating the asset harshly like over-speeding. Accelerated relates to neglect or doing nothing like not lubricating the rotating components.

Out of the total failures, further stratification of the failure data yielded that 83% of recorded failures were attributed to natural deterioration, whilst 17% was considered as forced/accelerated deterioration. Forced/accelerated deterioration was mostly attributed to lubrication starvation, dirt accumulation on equipment, and incorrect dimensional fits. This resulted in a project to review all preventative maintenance (PM) schedules for all assets that were analyzed and to make sure that appropriate maintenance tasks such as routine lubrication were being carried out as per the scheduled PM.

PM schedules review was carried out on 92% of physical assets that were under study, and 8% of the physical assets underwent modifications related to structural make-up, dimensional changes, design changes, material strengthening and lubricant specifications changes.

The maintenance actions taken in response to components deterioration witnessed a downward trend in monthly downtime hours from an average of about 30 hours per month down to around 16 hours monthly. This was a drastic 47% drop in total plant downtime due to the targeted maintenance actions that were taken to lessen the impact of equipment failures due to deterioration.

## 5. Conclusion

The key to improving physical assets reliability in any industrial set up is firstly, undertaking an analysis of the key drivers of equipment unreliability. The dominant failure modes need to be unveiled and further stratified in order to reveal the underlying causes of functional failures of the physical assets. The case study that was undertaken illustrated that without accurate data analysis, it is highly possible for a business to focus its resources on nonexistent or insignificant issues that do not address the inherent reliability issues that are relevant during that time. The data analysis showed that components deterioration was the major contributor to equipment failures within the processing plant, and it was prudent to develop reliability improvement strategic models that aimed at eradicating or diminishing the impact of deterioration on the components of physical assets.

Deterioration is inevitable in physical assets components, whether they rotate, slide or are stationary during their operational status, because one way or another, the agents that cause deterioration will attack them. Unless the physical assets operate in a vacuum, that is the only scenario that maybe have them spared from deterioration. Different types of deterioration were examined during this research, and prominently corrosion and erosion types of deterioration were reviewed, with techniques of counteracting their progression discussed as well. More research need to be undertaken in developing scientific models to counteract deterioration in the industrial setup.

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## Biographies

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