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Rinser Machine and the Dynamics-based Failure Analysis for Spur Gear Fault Detection: A Forensic Review

Amanda O. Orhevba, Enesi Y. Salawu*, Oluseyi O. Ajayi, Anthony O. Inegbenebor, Richard O. Leramo, Joseph O. Dirisu and Sunday A. Afolalu

Department of Mechanical Engineering, Covenant University, Ota, P.M.B. 1023, Ogun State, Nigeria.

*Corresponding author's email: enesi.salawu@covenantuniversity.edu.ng

Abstract. Gear fault detection and its severity is essential for analyzing the availability, maintainability and reliability of rinser machines. The occurrence of multiple failures of gears and their analysis is becoming more challenging, thereby causing the increased unavailability of rinser machines. This study reviewed the rinser machine and its various advantages and disadvantages, including the problems associated with the machine. More so, various types of failures associated with the spur gears were studied, and it was established that the detection and the diagnosis of gear faults would inform a maintenance planner on scheduled maintenance. Thus, the absence of failure detection will cause uncontrolled machine breakdown and, consequently, result in unsafe operation as well as a loss of productivity. The study concludes and recommends grey cast iron as alternative material that could reduce chemical failure and failure resulting from fatigue.

Keywords: Gear failure, rinser machine, reliability, fault diagnosis, grey cast iron

1. Introduction

Gears are elements of a machine that are used in the transmission of power and motion between rotating shafts. They are essential for power transmission in a lot of present-day machinery (such as industrial, energy, automotive and aircraft sectors). They are prevalent as they have the edge over other power transmission elements due to their high capacity for load, high efficiency, and how diverse they can be in their sizes [1][2]. During the gear selection process, there are multiple factors to be considered, including the area of application, the gear type, and the manufacturing material. Due to the varying mechanical and chemical characteristics of different materials, the material from which the gear is produced is a significant factor [3][4]. For instance, a brittle material cannot be used in a high-stress environment, as it would break easily under pressure. Material properties, however, can be improved upon with various techniques, some of which include carburization and heat treatment for some metals [5][6]. There are multiple kinds of gears and the spur gear, being the most economic to manufacture, is more often used. However, due to contact in the point of mesh, there is a tendency for noise while in operation. However, it is imperative to derive methods for the reduction of this noise and wear [7]. A rinser machine is one of such machines that use gears, specifically spur gears, in the transmission of its required motion. Rinser machines are used to clean and sterilize jars and bottles and various containers for intended use, usually used in the beverage, bottling, and packaging industries. One problem usually associated with the gears in this machine is that they are constantly under vertical loading caused by the weight of other moving components and therefore susceptible to failure for this reason. An anomaly that often occurs during its operation is the repeated fatigue failure of the spur gear teeth. Failure of its gears and gearsets could also be prompted by other operating conditions such as ambient temperature and fluids used in the machine; now this gear failure, in turn, results in repeated downtime and delayed production [8-9]. In some instances, bending fatigue stresses that exceed their material strength have caused tooth breakage and fracture of spur gears [8]. In addition, gears can also fail due to stresses at their contact surface, and the failure happens at this surface [10]. Due to this, developing an understanding of the dynamics concerning this surface is imperative to tackling relating problems [11].

Pitting is a common material failure which usually occurs on a gear tooth contact surface. Thus, backlash is usually used to reduce the noise and vibration on the gear tooth [12-13]. These damages would negatively affect the systems in which these failed gears are present and may bring these systems to a halt or cause severe damage to the machines, subsequently incurring significant economic losses. In more critical situations, there might even be loss of life. Thus, all faults of whatever type in gears and gear systems must be accurately detected, traced and then controlled [14]. It is imperative, therefore, to note that to accurately manufacture a gear part, it is necessary to select the design criteria of the gear. This is based on the design specifications of the part and the system in which it would be needed [5]. Grey cast iron is quite an ideal material for use in engineering due to how cheap it is and the ease with which it can be machined. Moreover, it happens to be the oldest and most common cast iron form. 'Grey cast iron' happens to be a wide term referring to various cast irons in which carbon is present in their microstructure—in the form of graphite flakes [15] [16]. These flakes, in turn, make the cast iron softer, easily machinable with self-lubricating properties, and less brittle when compared to white cast iron. Due to its ability to be very fluid in a molten state, cast iron is highly suitable for the production of complex castings. The resistance of grey cast iron to corrosion seems, by all accounts, to vary. This variation, however, is highly likely to be dependent on its production method [17] [18]. Grey cast iron, like all graphitic irons, demonstrates high damping capacity, as vibrational energy is dispelled at these internal interfaces. Grey cast iron is also strong in compression, and as for many applications, compressive strength is a much more critical factor compared to tensile strength. In a lot of cases, grey cast iron compared to steel performs much better in applications with compression-loading [16].

Due to these factors, gears made of grey cast iron are highly favourable. However, because of variations in operating conditions, it is necessary to determine the behaviour of these gears in specific conditions and how those behaviours affect the overall operations of machines, and for the case of this study, of rinser machines.

2. Rinser Machines

In bottling and packaging industries, it is necessary to maintain the containers used for packaging at specified health code levels. This is because some of these containers are being recycled and reused, and therefore need to be thoroughly cleaned before they can be used. Also, for newly manufactured bottles and containers, the manufacturing process might not provide these containers with adequate levels of cleanliness, so there is a need for additional cleaning measures before they can be used. For this booming industry, production rates would be significantly reduced if this were to be accomplished manually. This develops a need for small-scale to industrial-sized machines that could fully or partially automate this process [19] [20]. Following this need, various sizes and types of rinser machines have been produced to aid in the automated cleaning of containers for bottling and packaging companies. The machines differ based on the sizes of containers they are required to clean and their modes of cleaning. Rinser machines are therefore mechanical devices that automatically or semi-automatically aid in the washing, sanitizing, and overall cleaning of packaging containers.

2.1. Rinser Machine Types

Rinser machines can be classified on three (3) main bases:

i. Based on the working fluid
   - Air Rinser Machines; in which the primary fluid used for cleaning is air.
   - Water/Liquid Rinser Machines; in which the primary fluid used for cleaning is water or any other appropriate liquid.
   - Dual Rinser Machines; in which both water/liquid and air are used as cleaning fluid.

ii. Based on the automation process:
   - Semi-automatic
   - Fully Automatic

iii. Based on size
   - Small and Medium-sized machines; used in small-scale companies.
   - Industrial sized machines used; used in large industrial production lines.

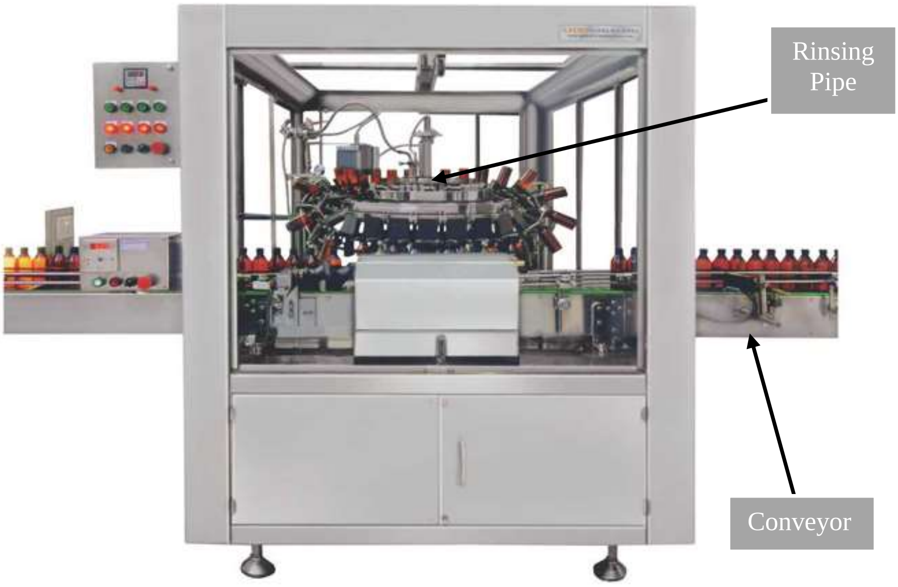

Fig 1: An industrial rinser machine
Source: Adapted from [21]

2.1.1. Applications of Rinser Machines. Rinser machines are useful in the cleaning and sterilization of equipment for various sectors and industries, and these include:

- Recycling plants for various bottles and containers
- Breweries for glass and plastic bottles
- Wineries for wine bottles and containers
- Water production companies for PET bottles
- Pharmaceutical companies for sterilization of containers

2.1.2. Problems Associated with Rinser Machines. Like in most machines requiring transmission of motion, most rinser machines contain multiple gears and gear sets necessary for their operation. Due to the conditions under which these rinser machines operate, such as temperature and fluids which are used in or around the machines, these gears are highly susceptible to failures such as corrosion, wear and fatigue failure owing to these conditions. It is, therefore, necessary to design the material and profile of these gears to enable them to function properly under these conditions throughout their service life.

3. Gears

Gears happen to be the most common mechanical system of transmission. A gear is a cylindrical component which is usually toothed based on the type of application. These toothed components may be in the form of wheels, worms or racks. Dudley, as cited in [7], defined a gear as "a geometric component which has teeth spanned around its entire circumference" Gears are transmission components with greater advantages compared to belt drives. Numerous conventional and advanced gear manufacturing methods are available for usage in particular applications in order to create fit-for-purpose gears. Over the last few decades, technical developments in gear engineering have allowed for the manufacture of high-quality gears with a near-net form having shorter process chains with reduced environmental impact [7]. Today, gears can be found in almost every area of endeavour with the advantage of operating at very high efficiencies.

3.1. A History of Gears

The 'Antikythera' mechanism which is over 2000 years old and from ancient Egypt, was built using gears. At this time also, motion was transmitted using spur wheels to aid the irrigation farms using gear enabled machines. Following this, gears were used in wind and water-powered devices to improve the rotational velocity of the pumps of windmills or watermills [22] [23]. In the 15th century, Leonardo da Vinci began inventing gears with the spur wheel. He developed new gears, as well as new discoveries about the superposition of independent movements. His sketchbooks, dating to the mid-1400s, illustrate a variety of distinctive gear mechanisms. Originally, the preferred material to be used in gear manufacturing was wood before cast iron took its place. Then, around the 1400s, a more sophisticated idea regarding gear innovation arose, introducing a wider application of sciences to gear design and related mechanisms [7]. By the 18th century industrial revolution in England, clocks, irrigation devices, water mills, and driven machines all used cycloidal gears. With the advent of locomotives, automobiles, and other devices, new applications of gears were quickly developed and explored. The company Benz created the first motor with a chain gear and sprocket gearing transmission, this was patented after 1882. However, two British men known as Starley and Hillman owned the first patent alluding to gears and gearing wheels [22]. By the early 19th century, technologies for gear hobbing and shaping were developed, laying the groundwork for the development of higher-quality commercial gears. From 1912, there began to be distinctions in industrially manufactured gears and wheels. During the late 19th and early 20th centuries, developments in gear production, measuring methods, and testing technologies paved the way for substantial growth in its industrial applications. In today's industrial world, gears are now used everywhere, in industries ranging from automotive, energy, electronics and more [24].

3.1.1. Classification and Types of Gears. A vast array of gear types is available to satisfy various user needs. Gears and gear systems are commonly categorised based on the arrangement of their axes of rotation. Based on this, gears are categorised as:

i. Parallel Shaft Gears: This is the most prevalent type of gear which has shaft axes that are parallel and co-planar. The teeth of this gear could either be straight and parallel to the shaft axis—called a spur gear—or they could be inclined—called a helical gear. These teeth could also be configured either externally or internally. These types of gear can be of a cylindrical or linear form and could be used in three different kinds of arrangements based on transmission: external, internal, and rack & pinion.

ii. Intersecting Shaft Gears: The shaft axes intersect in this gear arrangement despite being in the same plane. The system in which two gear shafts that are engaged are at 90º to each other—known as the right-angle system—is the most common configuration. Conical-shaped bevel gears are the best option for this right-angled configuration. The straight and spiral are the two basic bevel gear types.

iii. Non-Parallel, Non-Intersecting Shaft Gears: The shaft axes of these noncoplanar gears can be set at any angle between 0 and 90˚. The most common gear types in this group are the worm type gears, hypoid gears, and cross-helical gears.

Table 1: Classification and Types of Gears

	Categories of Gears (Based on Orientation of the Gear Shaft)	**Types of Gears**
1	Parallel Shaft gears	Spur
		Helical
		Rack and Pinion
2	Intersecting Shaft gears	Straight Bevel
		Spiral Bevel
3	Non-parallel, non-intersecting shaft gears	Worm and Worm wheel
		Cross-helical (screw)
		Hypoid

Source: [7]

Figure 2: Some types of gears
Source: Adapted from [25]

3.1.2. Spur Gears. Spur gears are seen as the most basic and widely used type of gear as they are simple and cheap to manufacture and versatile for a wide variety of uses. They are used in motion transmission between parallel and coplanar shafts and, due to their form, are categorized as cylindrical gears [26]. The tooth profile in spur gears is straight and the axes of the mounted shafts are parallel to them. These teeth mesh one at a time and they have an involute profile. Due to this form, no thrust force is produced in the axial direction, i.e., spur gears only produce radial forces. If two spur gears are in mesh, the one with more teeth is referred to as the "gear", while the one with fewer teeth is referred to as the "pinion" [22] [24]. Spur gears materials are typically metals such as steel or brass; however, they can also be made from plastics such as polycarbonate or nylon. Plastic gears happen to be quieter, however, they lack the power and loading capability of gears made from metal. Multiple spur gears can be used in series (a gear train) to achieve high reduction ratios. There are two (2) main classes of spur gears: External tooth and internal tooth. External teeth gears have teeth that are cut around the cylinder's external surface, and they are the most common variety of spur gears. When external gears are in mesh, they are rotating in opposing directions. In contrast, internal gears have their gear teeth cut on the internal surface of the cylinder. An internal gear meshes with a pinion (a smaller external gear) which is housed inside its wheel, with these gears rotating in the same direction. The assembly of internal gears are more usually compact compared to that of the external gear since the shafts in the internal gear assembly are closer together. Spur gears are often considered to be the best choice in instances requiring the reduction of speed and multiplying torque, these include ball mills and equipment for crushing [27].

Fig 3: Spur gears in mesh

i. Advantages of Spur Gears

- Ease of manufacture
- They can be produced to high levels of accuracy and precision
- Absence of high losses due to slippage
- High efficiency of power transmission

ii. Disadvantages of Spur Gears

- High noise production at high operation speeds
- High stress at gear teeth
- Operate with a limited centre distance

iii. Applications of Spur Gears

- Used in aircraft engines
- Used in automobile engines
- Used in marine engines
- Used in Conveyor systems
- Used in various industrial plants
- Used in power plants

3.1.3. Gear Failure. Failure or improper operation of machinery and equipment can often be traced back to gear failure. Gear failures can be caused by a variety of reasons, and the consequences of gear failure are often detrimental to the equipment's operation and efficiency [28]. Various modes of gear failure are discussed below:

i. Polishing

Polishing occurs in well-lubricated gear surfaces that have been in operation for a significant length of time (Figure 4). After a significant period of operation, a uniform polish stretching from end to end and from root to tip of the gear tooth is an indicator of a well-designed, well assembled, and properly maintained gearset. Polishing normally indicates a minimal rate of wear, and unless the gears are subjected to an exceptionally high amount of mesh cycles over the course of their expected life, low rates of polishing are usually inconsequential. If early observation shows that the polishing indicates a significant amount of wear, a heavier lubricant or a lower lubricant inlet temperature might be considered. These improvements will aid in minimizing wear [29].

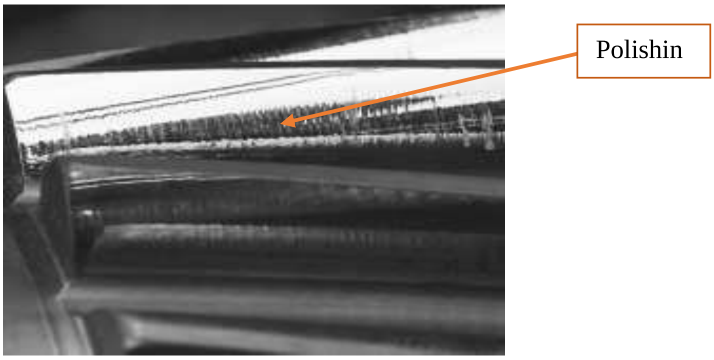

Fig 4: Polishing type wear
Source: Adapted from [30]

ii. Moderate Wear

Wear can occur at a faster rate than polishing if the lubricant film is not appropriately thick. In this type of wear, a ridge at the operating pitch line of the teeth becomes obvious. Moderate wear is visible as contact patterns in the dedendum and addendum regions where some sliding occurs. Since it is higher than the rest of the tooth, the working pitch line, a region where no sliding occurs, becomes visible. Frequent use of the gear induces this damage, and it is mostly unavoidable. Inadequate lubrication is also a common cause; however, contamination in the lubricant may also cause contact patterns to differ from the original pattern.

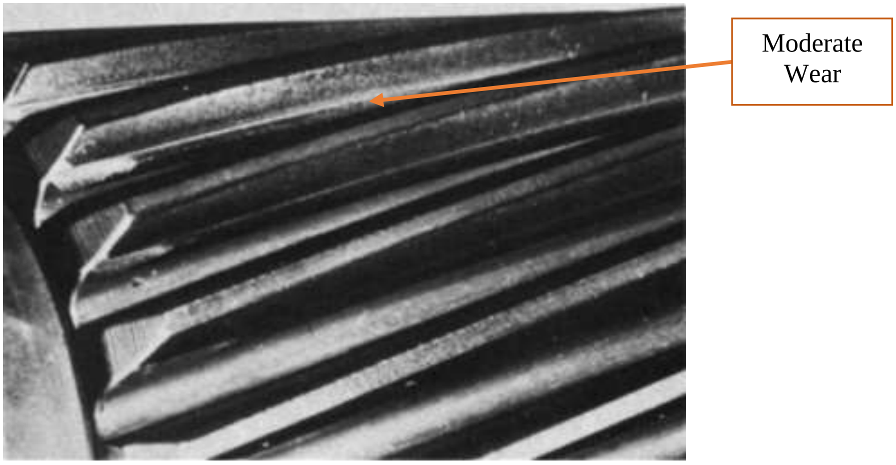

Fig 5: Moderate type wear
Source: Adapted from [29]

In certain cases, moderate wear can be managed by increasing the oil film thickness, as addressed with polishing. In the case of lubricant contamination, the lubricant needs to be filtered to a particle size smaller than the thickness of the film. Sufficient lubrication of the gear can reduce the harm caused by moderate wear. Scheduling routine checks to detect possible contact damage early is also advantageous. Moderate wear is usually not a concern except if it causes the gear to operate incorrectly due to vibration, breakage, or noise before the expected service life has passed.

iii. Excessive Wear

Excessive wear results from moderate wear that is left and allowed to cause more damage. If the rate of wear is high enough, enough material will be stripped from the teeth that they will either break off owing to thinning or become too rough to be acceptable, well before their service life is exceeded. Excessive wear could lead to pitting on the gear surface; this, in turn, causes vibration in the gearbox, which leads to higher noise production and gear damage. The best way to prevent excessive wear on gear surfaces is to address minor and moderate wear and tear early on so they do not aggravate. Changing to a harder material or changing the gear geometry can sometimes be necessary. If the gears showing excessive wear have a film-thickness ratio of close to or lower than 1.0, the wear can be explained as a result of friction contact. However, if the film-thickness ratio is closer to 4, evidence of abrasive wear or the presence of high loads as a result of prolonged vibratory or torsional movement should be the focus of the investigation.

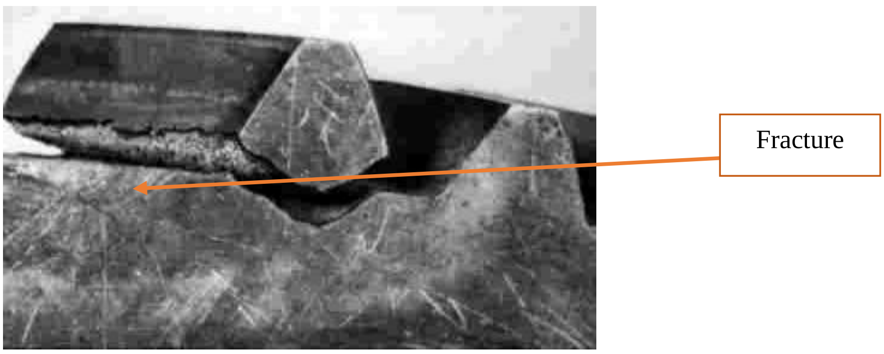

Fig 6: Excessive wear
Source: Adapted from [30]

iv. Abrasive Wear

Abrasive wear appears as radial scratch marks and other marks that indicate contact wear. In a manner similar to that of mild wear, when foreign substances are present within the lubricant it causes abrasive wear. This is one of the most common causes of abrasive wear. Metallic particles from the bearings and gear system, rust, sand, or weld spatter are possible causes of this problem [31].

Fig 7: Abrasive wear
Source: [30]

The lubrication causes abrasions on the gear surfaces, which can lead to an increase in vibration and noise, reduced reliability, and even failure of the gearbox. By changing the lubricant and keeping it clean, this form of gear damage can be avoided.

v. Corrosive Wear
This occurs through acid, additives or moisture in the lubricant [32]. Corrosive wear normally appears as fine, uniform pitting over a gear's surface. As lubricants chemically degrade, the resulting chemical debris attacks the metal in gears, causing corrosion. High-pressure additives in some lubricants often degrade at high temperatures, creating very active chemical compounds. When lubricants like this are in use in gear sets, they should be routinely checked to ensure that they are still suitable for operation. The use of modern lubricants that are produced to prevent breaking down will also help to prevent corrosion. Aside from within the lubricant itself, the active factors attacking the gear could also be from sources outside the gearset casings. If these sources are found to be external to the gear casing and its lubricant system, they could be entering through the breather, seals, or gaskets, in the casings, or through openings in the lubrication system. It is then possible to implement solutions to restrict further entry once the form of entry has been discovered. A change of gearset materials or special means of protecting the materials may be necessary for especially hostile environments [33].

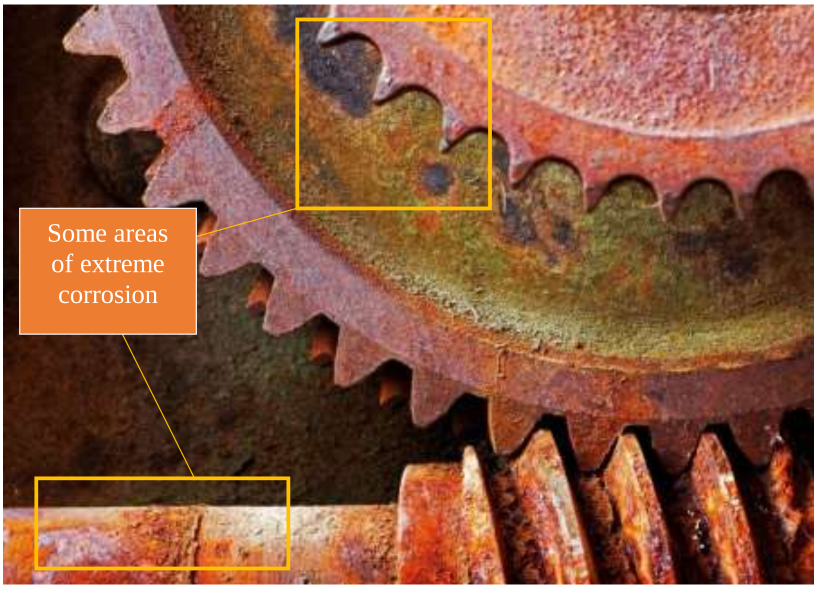

Fig 8: Corrosive wear
Source: Adapted from [34]

vi. Macropitting

Pitting or Macropitting is damage to the gear surface caused by fatigue accrued under cyclic loading [35]. It also affects other components whose surfaces undergo rolling/sliding contact under significant loading. The tooth root and pitch line are usually the most affected areas. Pitting initiates when microcracks caused by fatigue form, as a result of high-stress concentrations on the contact surface or subsurface; these cracks then expand and propagate as a result of repetitive cyclic loads until they cause material separation. Another possible cause of pitting is hydrogen metal embrittlement caused by lubricant contamination with water. Foreign particle contamination of the lubricant can also be responsible for it. Surface stress concentration sites are generated by these particles, which then reduce the thickness of the lubricant film and facilitate pitting. Severe macropitting alters the gear tooth profile, often triggering extreme vibration and audible noise, thereby eventually leading to breakage of the gear tooth. Pitting failure occurs in both through-hardened and surface-hardened gears; however, surface-hardened gears are more predisposed to exhibiting micropitting [36].

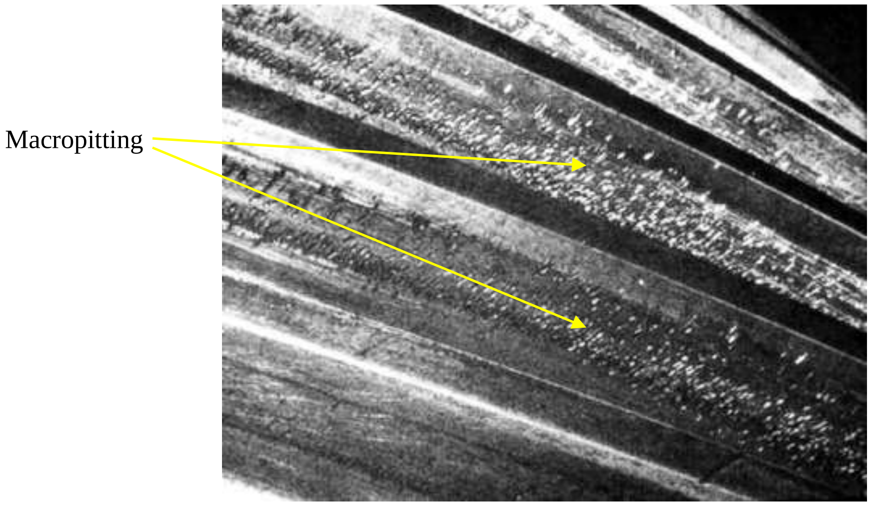

Fig 9: Pitting
Source: Adapted from [37]

vii. Micropitting

Micropitting, a type of surface contact fatigue-failure, is irreversible and is caused by the initial cracks which propagate into larger cracks in the direction opposite that of sliding. It leaves small pits on the tooth surface, usually below the pitch line in the area of negative sliding—short cracks on the surface become the nucleus of these craters, which gradually strip surface material. The structure of micropitting is similar to that of macropitting but with a different scale and characteristic diameter and depth. Since micropits characteristically scatter light, they give the affected area a frosted, light-grey look. Micropitting is a fairly new phenomenon that has become prevalent due to an increase in the use of surface-hardened gears of higher quality steel. It can be found in any heat-treated gear, but it is most common in gears that have been ground and whose materials have been carburized. Micropitting can also be caused by modern lubricants with special additives that enable gears to operate in severe conditions [38]. Micropitting can also contribute to tooth flank bending fatigue failures. As this failure progresses, noise and vibration levels in gearsets increase, and the profile of the gear tooth degrades. Furthermore, micropitting and the resulting surface cracks are often candidate locations for macropitting and can result in spalling. Both macro and micropitting can be curbed by constant maintenance and checks of gearbox operations. Other procedures that can help reduce the onset of gear pitting failure include the reduction of contact stresses by reducing loading or the optimization of gear geometry. Also, the hardness of steel can be increased with proper heat treatment or carburizing. It also helps to use the right amount of cool and clean lubricant with the appropriate viscosity [39].

Fig 10: Micropitting
Source: Adapted from [39]

viii. Spalling

This type of damage is similar to pitting but is shallower and with a larger diameter (See Fig 10). Spalling is more non-uniform and occurs in high-contact areas where the gear material experiences stress. Generally, in spalling, a large region of surface material breaks away from the tooth. Spalling appears as a massing of several clustered large pits in one region in through-hardened and soft materials. It, however, manifests in surface-hardened material as the removal or depletion of a single or multiple large regions of material.

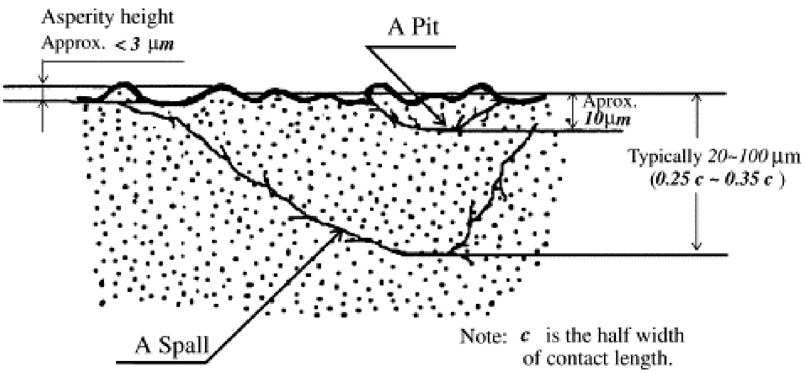

Fig 11: Spalling and Pitting Phenomena
Source: [40]

Spalling generally indicates that the gearset is loaded in excess of the capabilities of the gear geometry or materials [29].

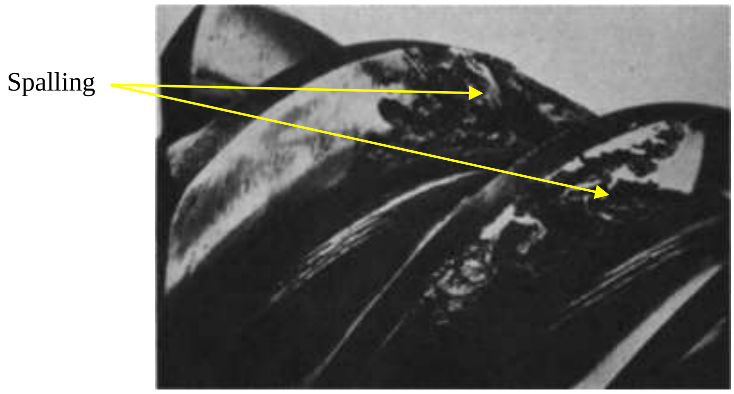

Fig 12: Spalling of a hardened pinion
Source: Adapted from [29]

ix. Scoring

Scoring is a failure which occurs on gear teeth in relative motion. It causes welds in metals in contact whose surfaces are not protected [41]. Metal particles separate from one or both gear teeth in mesh to the other, and these metal particles will attack the flanks of the gear teeth in the sliding pitch surface during the gear operation. It can be sometimes difficult to tell the difference between surface scratches caused by rapid scoring and those caused by wear.

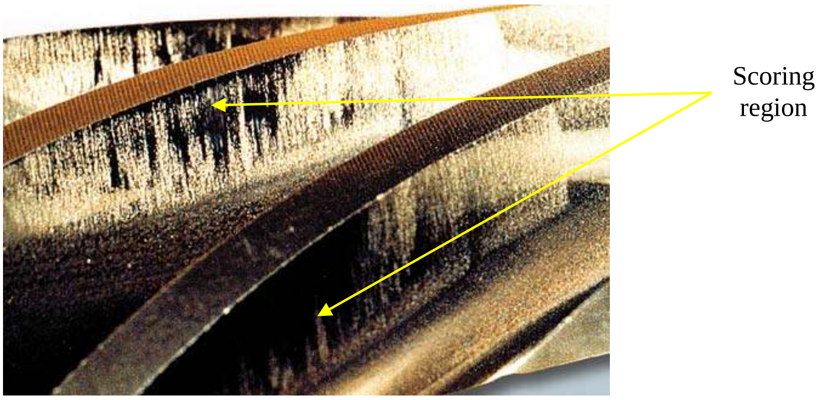

Fig 13: Scoring
Source: Adapted from [30]

Scoring is dependent on the lubricant and lubricating conditions as opposed to the gear material properties such as strength. Scoring can be prevented with a protective layer of lubricant, which would help avoid direct contact between the metal surfaces. This layer may be a dense oil film or a layer formed by lubricant additives that are adsorbed or chemically deposited. When a lubricant degrades with time or becomes contaminated with metal particles or water, the risk of scoring increases.

x. Fracture

The most severe form of gear failure is fracture. This is a form of failure in which a whole tooth, part of a tooth, or many teeth, break off from the gear blank. It usually leaves indications of the focal point of the fatigue that resulted in the fracture. Fracture occurs when certain load stresses exceed the material's strength or when a large number of repetitive stresses exceed the material's endurance capacity [29]. Thus, not controlling the stress could cause serious damage to the gear tooth [42][43].

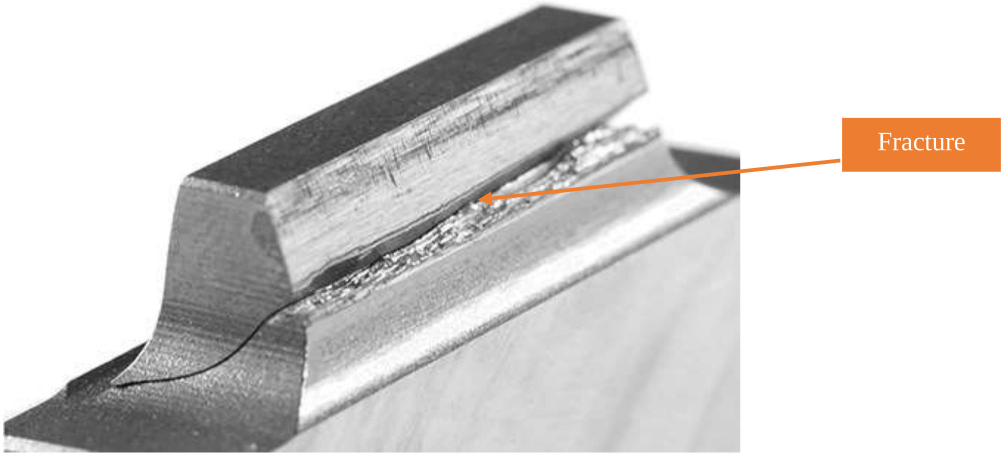

Fig 14: Tooth flank fracture
Source: Adapted from [28]

4. Cast Iron

Cast Iron refers to a grouping of ferrous alloys, which are iron alloyed with over 2% carbon and between 1%-3% silicon. The level of alloying with concurrent regulation of the tempering process yields a very diverse range of properties giving varying grades of cast iron. Due to cast iron being very fluid in its molten state, it has high castability, hence its name. Cast iron is hugely favoured as a material for various reasons, including its good castability, ease of procurement, and high compression strength compared to steel [31]. It is very appropriate for many machine frames as it possesses good damping properties. However, cast iron's resistance to impact and ductility are usually limited, which limits its application [44]. Cast iron has and continues to have a variety of applications in various industries ranging from the production of machines, automobile parts, pipes, and kitchen equipment, amongst other things.

4.1. Cast Iron types

Categorically, cast iron is divided based on its microstructure, which in turn is dependent on various factors. These factors include the concentration of carbon present, its level of impurity and the rate of cooling during the process. The properties of cast iron are determined by the state and structural form of carbon present in its microstructure. The configuration and composition of the carbon present in cast iron are adjusted to give either *White, Ductile* or *Grey cast iron*. The mechanical properties and machinability of these different types of cast iron vary considerably [45]. The approximation of the impact of carbon and silicon on the solidification of cast iron from the melt is determined by a quantity known as carbon equivalent (CE). This carbon equivalent shows which cast would cool into grey iron—microstructure containing graphite—and which would give white iron—carbon present in the form of carbide. This variation in the cooling rate results in either white or grey cast iron [16].

4.1.1. White Cast Iron. The only cast iron type that contains carbon strictly in carbide form (as cementite) is known as white cast iron. It also has low silicon content and is created by the solidification of solute carbon making it unable to form graphite. When rapidly cooled from a melt, graphite does not form, and the microstructure consists of austenite dendrites in a eutectic (iron carbide and austenite) matrix. When austenite starts to cool to room temperature, it breaks down into eutectoid pearlite [16]. White cast iron is dubbed so because of its white surface look—caused by the absence of graphite—at fracture points because of carbide impurities, which permit cracks to propagate. It has great compressive strength while also maintaining its strength and hardness at high temperatures, however white cast irons are quite brittle. Because of the various carbides within—depending on the alloy level—these cast irons are tough and wear-resistant but have low machinability. White cast iron regularly finds use in roller crushers, ball mill liners, lifting bars and other applications requiring high hardness and [46].

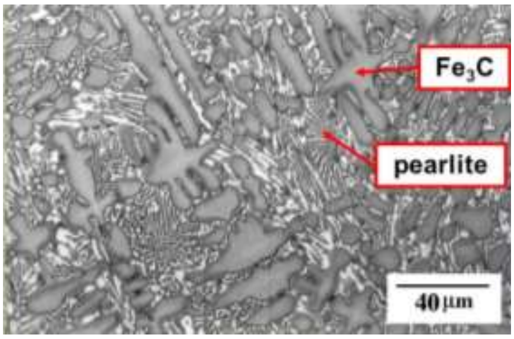

Fig 15: Microstructure of white cast iron
Source: Adapted from [47]

4.1.2. Nodular Cast Iron (Spheroidal Graphite Cast Iron)
This is a form of cast iron that has graphite present in a spheroidal shape. Nodular cast iron is obtained directly from the solidification of molten cast iron—with the addition of cerium or magnesium to the iron before the casting process—and it requires no post-cast heat treatment [45].

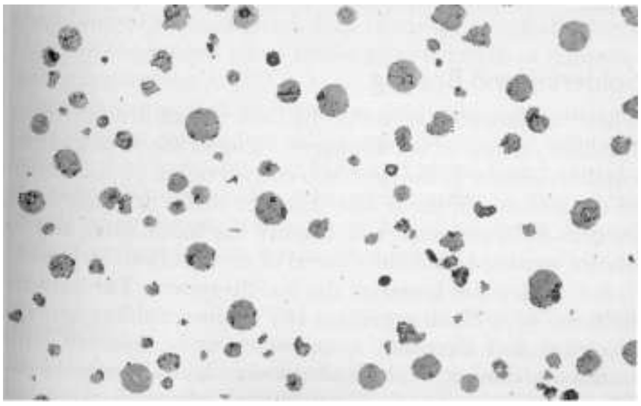

Fig 16: Micrograph showing spheroidal unetched graphite in cast iron [45]

The graphite spheroids form when, during solidification, there is a separation of the eutectic graphite from the molten iron, with additives assisting the graphite in taking on a nodular shape. Nodular cast iron possesses great tensile strength with good elongation properties, finding applications in machine parts used in the wind and energy industry, amongst others [48].

4.1.3. Grey Cast Iron. The oldest type of cast iron is grey cast iron. Due to this, it is wrongly believed by many that it is the only cast iron; therefore, cast iron has been interchangeably named grey iron. Grey cast iron is referred to as cast irons whose microstructure contains flake graphite in the ferrous matrix. The formed eutectic is made up of graphite flakes and austenite. The combination of silicon present in the melt and slow cooling conditions promotes the formation of graphite rather than iron carbide. This form of cast irons frequently comprises about 2.5 – 4 % carbon content, 1 – 3 % silicon content and meagre amounts of manganese additives [49]. The matrix of this metal has embedded carbon within it—in the form of flake graphite—in phases of ferrite, pearlite, or various combinations of the two.

Fig 17: Micrograph of grey cast iron showing graphite flakes in a ferritic matrix

Grey cast iron is definitively softer due to its microstructure when compared to other cast iron forms. Because the present graphite flakes of large size diminish its ductility and strength, inoculants are employed to induce finer flakes. The presence of graphitic flakes heavily influences the mechanical properties of grey cast iron. They act as stress concentrators, which could result in premature localized plastic flow in low-stress conditions and matrix fracture at high-stress conditions, i.e., making the materials lack toughness. Grey cast irons are noted for having tensile strengths ranging from 20ksi to 60ksi—according to ASTM A-48—with 40ksi and above irons being referred to as high strength [29]. Therefore, grey cast iron displays little elastic behaviour as it fails under tension without substantial plastic deformation. Grey cast iron also has high machinability, excellent self-lubricating qualities and good damping properties due to the presence of graphite flakes. These irons also excel in situations involving much wear as the present graphite aids in the retention of lubricants. Furthermore, because of the fluidity of molten grey iron and the way it expands during solidification—as a result of the graphite formation—this metal is suitable for cost-effective manufacturing of complex castings with no shrinkage [50]. Grey cast iron is a prominent engineering material applied in a myriad of applications due to its low cost and ease of machining. They have many properties that make them a very desirable material for engineering applications, and among these include their high compressive strength, and ability to resist deformation and make rigid structures. Also, their low melting points—about 1140°C-1200°C—enhance castability, allowing them to be used for complex and intricate designs easily. Their excellent vibrational damping characteristics make them a major choice for frames and housing for many mechanical devices. Grey irons possess high thermal conductivity—ease of heat transfer through them. Grey iron castings are also well adept at withstanding thermal cycling, which is the constant switch between higher and lower temperatures of a component that can cause stress and initiate failure in some materials [51]. These irons are also very resistant to oxidation, so failures due to corrosion are greatly reduced. Grey cast iron is typically considered and used in situations where the necessity of rigidity outweighs the necessity of tensile strength. Applications, where these properties of rigidity, ease of machining, high thermal conductivity, high heat resistance and damping are required, include engine blocks used in ICE (Internal Combustion Engines), flywheels, manifolds, various kitchen equipment and disk brake rotors. In addition, due to grey iron's ability to withstand heavy loads and resist corrosion to a certain degree, it is adequate for applications such as the construction of cinderblocks (for construction), pump and turbine housings, gears, valves, various automotive suspension components, couplings, as well as numerous other things. Also, almost all manhole covers are constructed of grey cast iron.

Fig 18: Image showing various applications of grey cast iron
Source: [52]

Fig 19: Gears made from grey cast iron
Source: [53]

5. Reliability Predictions of Bottling Machine

Reliability prediction of engineering components/systems is important in evaluating failure rates as well as establishing models for subsequent failure analysis [54]. For instance, Salawu et al. [55] established that the mean-time to failure of bottling machines which are connected in series can be described by equation (1) below, where the failure rate was assumed to be $\lambda = 0.04$ for the respective unit in each of the bottling machines.

$$MTTF_s = \frac{1}{\sum_{j=1}^{k} \lambda_j}$$

Equation 1: mean-time to failure of bottling machines

The study established that the reliability of the plants reduced with the operating time. Also, it is important to understand that quality control and assurance in a manufacturing sector contribute immensely to the functionality as well as the reliability of the product [56-57]. Thus, it is important to improve the system's reliability in order to achieve overall productivity during production.

6. Conclusion

The available literature on gear failure detection and analysis has been technically summarized in this study. To help with the understanding of the studied literature in this article, the study was narrowed down to spur gear failures in rinser machines for the purpose of determining the reliability of the machine. Furthermore, grey cast iron properties were highlighted and recommended for gear production. Thus, equipment availability, maintainability and reliability will cause greater productivity.

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