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Research Article

DETERMINATION OF POSSIBLE CAUSES OF MISS ROLL (COBBLES) IN STEEL ROLLING INDUSTRIES IN NIGERIA

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Abstract

Three steel rolling mills in Nigeria, tagged A, B and C were visited in order to determine the potential causes of miss roll (cobbles) in steel rolling industries in Nigeria. Test rolling was carried out in each mill. Prior to the test rolling, the mill train was thoroughly inspected and all the necessary maintenance on the mill train was carried out. When all the conditions were confirmed satisfactory, test rolling was then carried out and the rolling process was observed along the mill train. Each time cobble occurs; production was stopped momentarily until the cobble was removed. Then the mill train was again inspected within the ten rolls closet to the point of cobble incidence. The defects observed were recorded accordingly. A probability model was proposed for predicting the possible causes of cobble based on the observations. In the model, a term referred to as probability index, (PI) was used to evaluate the chance of each detected defect causing cobble. From the results obtained, worn-out rolls, distorted rolls, cracked rolls, worn-out dies, die blockage and roll misalignment were frequently observed after cobbles incidence with probability indexes of 0.5000, 0.5000, 0.0455, 0.0909, 0.1818 and 0.3182 respectively for Mill A; 0.2470, 3764, 0941, 0.1529, 0.1765, and 0.2470 respectively for Mill B; 0.3796, 0.3396, 0.0799, 0.1198, 0.1099 and 0.2497 respectively for Mill C and 0.3688, 0.4044, 0.0745, 0.1361, 0.1535 and 0.2826 respectively for mills A, B and C put together. Zero probability indexes were not recorded in any case; thus, all the mentioned defects are potential causes of cobble. Microsoft Excel ToolPak (2010 version) was used to conduct Chi-Square test at 0.05 level of significance to determine the association between the defects and cobble. The result of the Chi-Square test shows statistically significant association between the defects and cobble (p = 0.0003). Average cobble rate of 4.5% was determined; indicating that about 4.5% of the billets ejected for rolling would form cobble. The result of this study will be a vital tool in steel rolling industries for taking proactive measures against cobble incidence. It will also be used to set standard for comparing the conditions of the mill train of various rolling mills.

Keywords: Defect, Probability, Cobble, Steel Rolling.

INTRODUCTION

Rolling is a metallurgical operation by which a workpiece is rolled out into desirable size and shape by passing it through rolls [1]. It is a common method used in manufacturing steel bars from billets and ingots. However, rolling operation is associated with a lot of hazards. Cobble formation is one of the most dangerous cases encountered in steel rolling. Steel cobble is red hot steel that drifted away from the right path and continued moving in awkward manner in rolling operation. Its consequences are numerous, which include sever injury, death, damage of mill equipment, structural damages, etc. All the consequence of cobble incidence amounts to economic loss. Cobble occurs accidentally without a warning sign. Therefore, it will be of interest to investigate the causes of this menace in order to proffer technical solutions to it. In most rolling operations, the workpiece is usually passed through two rolls known as the work rolls, which may be supported by other rolls known as the back-up rolls. The workpiece is passed through the work rolls under an applied pressure known as rolling load such that the emergent product takes the size and shape of the die. There may be need to preheat some metals in order to soften them before rolling. This practice usually helps in reducing the required rolling load. However, some metals are soft and ductile, such as aluminum, copper and pure iron and may not require preheating prior to rolling. Based on this consideration, metal rolling is basically classified into two, namely hot rolling and cold rolling. Generally, the term hot working means the working of a metal at a temperature above the recrystallization point while cold working is the working of a metal at a temperature below its recrystallization point. Alcelay *et al.* [2] gave illustration on hot working behavior and processing maps of duplex cast steel while Olivia [3] gave explanation on different types of cold working metal processes. Hot rolled products usually have poor surface finishing while cold rolled product often have good surface finishing but require relatively high rolling load. Since cold working temperature is relatively low, internal stresses are often introduced into cold rolled product due to the dislocation movement. The cold working temperature is usually insufficient for stress relief. Consequently, this makes cold rolled products to have relatively high strength and hardness. In order to improve the mechanical properties of cold rolled metal products, the products are usually subjected to stress relief anneal known as recovery. In Recovery process, the metal is heated up to a temperature below the recrystallization point and held to a reasonable time until the strength and hardness of the material reduce to desired extent. The duration of pre-heating of the work piece (known as soaking time) depends on the size of the

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workpiece, the magnitude of introduced internal stress, desired mechanical properties, etc. A typical example of stress relief anneal (recovery) was given by Rajat *et al.* [4]. Other criteria for classification of rolling process include the type of the rolled material, shape of the product, arrangement of rolls and type of the job done. According to JSW Steel [1], classes of rolling systems based the rolling jobs include ring roll [5], roll bending [6], profile rolling [7] and controlled rolling [8].

Ring roll

Ring rolling is a continuous roll forming process by which the workpiece is passes through a set of rolls specially arranged for manufacturing of ring shape products with desirable qualities [9]. It is an advanced technique used for manufacturing seamless rings with flexible cross section and improved grain structure. Ring rolling is used for production of railway, anti-friction bearing races and ringed shaped workpiece for automotive and aerospace applications [9]. Figure 1 is a schematic illustration of ring rolling system.

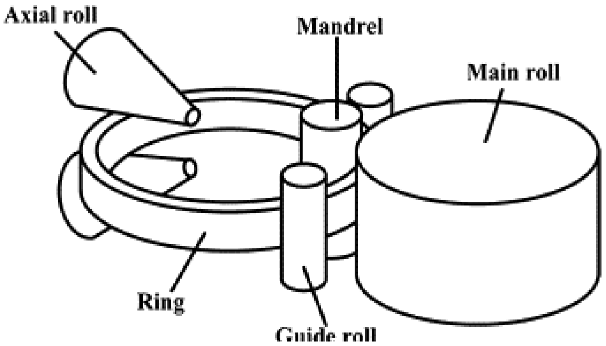

Figure 1. Schematic illustration of ring rolling system [9]

Roll bending

Roll bending is a three point metal forming process used extensively for wide range of applications in several industries such as oil and gas, naval and automotive. It is used in cylinders and truncated cones bending [10]. Roll bending is illustrated in Figure 2.

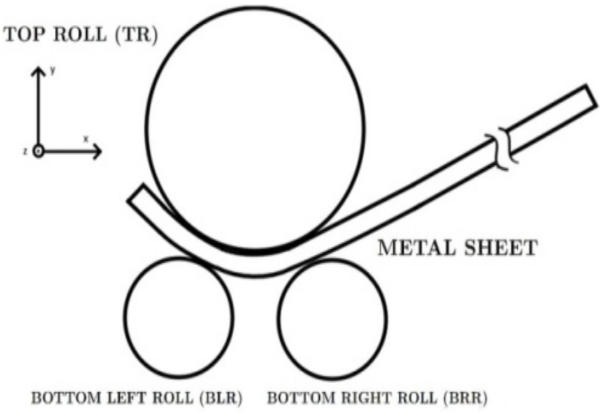

Figure 2. Schematic illustration of roll bending process [10]

Profile rolling

Profile rolling is a roll forming process in which the workpiece is passed through series of rolls that gradually shapes it into the required profile as shown in Figure 3. The profile rolling is basically used for manufacturing long metal profiles.

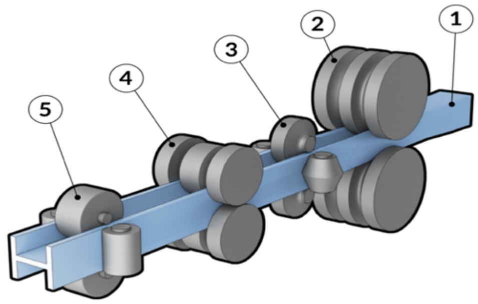

Figure 3. Schematic illustration of profile rolling system [11]

In profile rolling, the workpiece (1), typically a bar, is first fed through a pair of rolls (2) to form a coarse beam. The beam is then passed on through multipurpose adjustable rolls (3) that have vertical and horizontal members. The workpiece then passes through roll (4) which ensures the upper and lower edges of the workpiece are parallel. The beam then goes through other multipurpose rolls (5) from which products of desired shapes, sizes and surface conditions are obtained [11].

Controlled rolling

Controlled rolling is an advanced rolling process in which the mechanical properties of the workpiece such as strength and toughness are improved in the rolling process [12]. Temperature is a major determinant of the microstructure of hot worked metals as microstructure is a major determinant of the mechanical properties of a material. In controlled rolling, the improvement of the mechanical properties of the product is achieved by controlling the rolling temperature. For steel rolling, an increase in the last-pass rough-rolling deformation in the austenite recrystallization temperature region refines the austenite grain size after rough rolling and finish rolling [12].
Irrespective of the considerations taken in design of rolling mills, malfunctioning of rolling mill equipment and sudden failure frequently occur. LIAONING MINERAL & METALLURGY OF GROUP [13] stated some common problems of rolling rolls, which includes cracks, peeling, make pits, sticking, broken roll, etc. These defects are often observed in steel rolling. However, one of the most frequent and the most dangerous forms of failure in steel rolling is cobble.

Cobble

Cobble, sometimes referred to as miss roll has been identified as the major concern in steel rolling [14]. It is a red-hot metal which deviated from the mill train in rolling operation. It is often caused by malfunctioning of equipment along the mill train. However, metallurgical flaws in the workpiece, such as cavity, blow holes, and dimensional defects (such as poor billet rhombodity) can increase the chances of cobble formation. Cobbles in steel rolling can lead to severe injuries, death, damage of equipment, structural damages, low productivity, etc. Unfortunately, cobble is a rolling accident, it does not show any sign prior to its occurrence. According to Rob [15] cobble occurrence is unpredictable. In the recent times, protective structures know as cobble guard [16] are constructed around the mill train to limit the travel distance of cobble in order to reduce the severity of the accident. Cobble incidence has been reported in previous studies [17, 18]. According to Kushal et al., cobble has adverse effect on the techno-economic parameters, which include mill utilization, material yield, mill productivity, overall equipment effectiveness, overall line efficiency, and specific heat consumption of the reheating furnace [14].

Motivation

The steel industry is one of the major sources of income of many countries of the globe and rolling mill is one of the major sections of the steel industry. Unfortunately, cobble accident has been identified as one of the major challenges facing the steel rolling industry all over the world. Its consequences are numerous and can lead to death and economic down turn. Thus, this work is motivated by the zeal to proffer a sustainable solution to cobble occurrence in steel rolling industries.

The main objective of this study is to investigate the causes of cobble on the mill train of steel rolling mills in Nigeria while the specific objectives include:

1. To identify mill defects that occurs on the mill train, within the limit of inspection.
2. To develop a probability model for predicting the chance of each defect causing cobble.
3. To determine the association between the identified defects and cobble, using statistical tool, such as Chi-Square test.
4. To state steel cobble mitigation measures based on the research findings.

Scope of the study

The hazards associated with hot metal rolling include cobble hazards [14], fires and explosions, lightening, dusts and fibers, carbon monoxide poisoning, steam explosion, slips, trips and falls, extreme heat hazard and burns [18, 19] but this paper is focused only on cobble. Engineering methods of inspection include visual inspection, destructive testing, non-destructive testing, dimensional inspection, mechanical testing, chemical testing, and etc. [20], but only visual inspection and dimensional inspection were used for this study. There are several steel industries in Nigeria; some are only rolling mills while some are integrated iron and steel industries [21, 22] but only three rolling mills, tagged A, B, and C were considered. Mill A is located at Odogunyan Ikorodu in Lagos Stale; Mill B, is located at Ogijo Ogun State and Mill C, is located at Aladja Delta State. Thus, this study covers only on three out of the 36 states of Nigeria. Different methods have been adopted in previous works for predicting causes of cobble, but only a proposed probability model is utilized in this study for predicting the potential causes of cobble in steel rolling.

Basic Principles of Rolling

The basic rolling principles have been described in previous related studies, such as Ikumapayi *et al.* [23]. Also, theoretical modeling and experimental study of dynamic hot rolling deformation have been explained by Tanbo and Yan [24]. The geometry of the rolling system, to a great extent determines the performance of the mill. Also, the metallurgical properties of the workpiece affect the effectiveness of the rolling system. Figure 4 illustrates the basic principles of rolling.

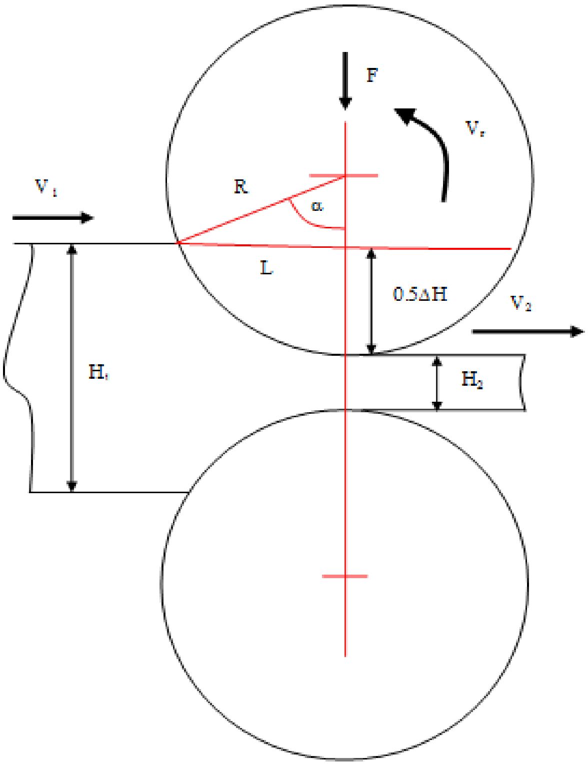

Figure 4.Basic parameters of rolling system

From Figure 4, the following deductions can be made:

$$L = R \sin \alpha \tag{1}$$

$$\cos \alpha = 1 - \frac{\Delta H}{2R} \tag{2}$$

Neglecting $(\Delta H / 2R)^2$ gives:

$$\sin \alpha = \sqrt{1 - \left(1 - \frac{\Delta H}{2R}\right)^2} \approx \sqrt{\frac{\Delta H}{R}} \tag{3}$$

$$L \approx \sqrt{R \Delta H} \tag{4}$$

$$\Delta H = H_1 - H_2 \tag{5}$$

where L is the contact length, α is the semi-contact angle and ΔH is the draft.

Maximum draft is given as Eq. (6)

$$\Delta H_{\max} = 2R(1 - \cos \mu_f) \tag{6}$$

From Figure 1, the forward slip of the rolling system is given by:

$$S = \frac{V_2 - V_r}{V_r} \tag{7}$$

where S is the forward slip, V_2 is the velocity of the product coming out from the rolls and V_r is the roll surface velocity.

The volume flow rate is kept constant under the condition and is given by:

$$H_1V_1W_1 = H_2V_2W_2 \tag{8}$$

where W_1 and W_2 are the widths of work piece before and after passing through the rolls respectively; H_1 and H_2 are the thickness of the metal before and after passing the rolls respectively; V_1 and V_2 are the velocities of the work piece before and after passing through the rolls respectively.

Rolling Pressure

Another determinant of the performance of a rolling system is the rolling pressure. It is the pressure exerted by the work roll on the workpiece. Rolling Pressure is expressed as the ratio of the rolling load to the contact area of the rolling system as given by Eq. (9).

$$\sigma = \frac{F}{w\sqrt{R\,\Delta H}} \tag{9}$$

where F is the rolling force (N) sometimes referred to as rolling load, w is the contact width and σ is the rolling pressure N/m^2).

The minimum strength required for the deformation of the metal, otherwise called mean flow stress is given Eq. (10) [25].

$$\sigma_{fm} = \frac{1}{\varepsilon_{\max}}\int_0^{\varepsilon_{\max}} \sigma(\varepsilon)d\varepsilon \tag{10}$$

where σ_{fm} is the mean flow stress, and ε_{max} is the maximum flow strain.

In order to account for the shape factor and plane strain deformation, rolling load is given by equation Eq. (11) [26].

$$P_r = 1.15\,Q_P\sigma_{fm}L \tag{11}$$

where P_r is the rolling load per unit length, 1.15 is the multiplier for plane strain, Q_p is the pressure intensification factor, L and σ_{fm} have their usual meaning. Pressure intensification factor, Q_p is calculated using Eq. (12) [26].

$$Q_p = \begin{bmatrix} \frac{\pi}{2}\sqrt{\left(\frac{1-r}{r}\right)}\tan^{-1}\sqrt{\left(\frac{r}{1-r}\right)} - \frac{\pi}{4}\sqrt{\left(\frac{1-r}{r}\right)\left(\frac{R^l}{h}\right)}\ln\frac{y}{h} \\ +\frac{1}{2}\sqrt{\left(\frac{1-r}{r}\right)\left(\frac{R^l}{h}\right)}\ln\left(\frac{1}{1-r}\right) \end{bmatrix} \tag{12}$$

where r is the reduction ratio, y the is the thickness of the metal at neutral point and h is the thickness of the work piece before passing through the rolls.

LITERATURE REVIEW

Several researchers have attempted to investigate into the causes of cobble while some have proposed methods of cobble prevention. The results of the studies seem to be positive although a perfect solution has not yet been found. Dhua *et al.* [17] investigated into the causes of premature failure of high-carbon steel wire rods during rolling. From the findings of the study, the failure of the hot rolled or controlled cooled, may occur as a result of improper rolling schedule, cobble, sudden mill stoppage and/or accelerations and processing inadequacies that lead to the formation of inappropriate microstructure.

Okechukwu *et al.* [18] developed of a method of operation for prevention of cobble formation in steel rolling mills; in the study, Delta Steel Company, Aladja Delta State Nigeria was used as case study. From the findings of the study, the four major areas billet derailment occurs are mill stands, shears, loppers and approach roller table along the mill train. He reported that malfunctioning of equipment on the mill rain can cause cobble formation. He also stated that cobble formation can cause loss of lives, damage of equipment, blockage of walkways, loss of materials (billet), loss of useful production uptime. Other losses include cost of cobble removal and cost of replacement of damaged parts. Looking at the consequences of cobble formation in rolling mills, there is need to identify the possible causes of cobble in order to determine the appropriate measures for mitigation of the incidence.

Rath *et al.* [27] gave the methodology for reduction of cobble generation at a Hot Strip Mill. In the study, the finishing strand of the mill was identified as the most critical area, where most of cobble generation occurs. Also, temperature variation across strip width was identified as one of the causes of cobble occurrence. As improvement strategy, the temperature variation across strip width was reduced by improving reheating furnace, descaler and roll cooling system. The analysis of mill signal was conducted using a supervised learning algorithm known as Support Vector Machine (SVM) to develop cobble prediction software in Visual Basic.Net (VB.Net) programming language. Real time data are being transferred from the mill Programmable Logic Controllers (PLCs) to WinCC servers using Object Linking and Embedding (OLE) for process control program. A web-client was developed for display of model prediction status. All these measures resulted in decrease in temperature variation across strip width from 25-30°C to 5-10°C and reduction of cobble generation by about 48%.

Kumar *et al.* [28] carried out investigated to identify the causes of chip formation through visual inspection and metallographic analysis of the bar samples collected at different stages of rolling. In the paper, it is stated that low-thickness bars (< 20mm) are prone to cobbles. It was also stated that blockage of slitter contributes to defects in rolling operation. Also, Kushal *et al.* [14] investigated into the causes of cobble in rolling operations by shop floor analysis and break down records at iron and steel rerolling mills. Based on the findings of the study, the root causes of cobble include electronic failure, high voltage, old drives, wear and tear, rust, etc. Mohamed *et al.* [29] presented taxonomy for biting cobbles during the hot rolling process in addition to a scientific study for determining its possible causes. The result of the study suggests that proper design of rolling system will reduce the chances of cobble occurrence. In such design, the frictional force between the workpiece and the roll must be equal to or greater than the horizontal component of the normal force [29]. In another article, Yoshikazu and Kazuo [30] statistically analyzed crack and spallings on work roll of hot strip mill finishing rear stands with emphasis on types of failure, roll operating and maintenance conditions for 80 pieces of damaged rolls. From the result of the study, cobble introduce crack on roll body which results in a small damage and quick roll change. Also, when the cracked roll is used continuously for rolling, more severe damage such as large spallings would be observed on the roll which suggests that spallings on rolls can cause miss roll (or cobble).

In the previous works, authors have given temperature variation across strip width [27], malfunctioning of equipment along mill train [20] and low-bar thickness [28] as causes of cobble. The result of the study conducted by Yoshikazu and Kazuo also suggests that cracks and spalling on roll can causes of cobble. Kushal *et al.* [14] have shown that the root causes of cobble include electronic failure, high voltage, old drives, wear and tear, rust, etc. Rath *et al.* [27] used Support Vector Machine (SVM) to reduce cobble rate. Okechukwu *et al.* [18] developed weekly reliability model for reducing the chances of cobble. None of the authors mentioned in this paper considered the physical defects (such as roll distortion, die blockage, roll cracking, etc.) as causes of cobble. Also, none of the authors considered probability as a tool for predicting the chances of cobble occurrence. Therefore, this paper proposes a mathematical model for predicting the possible causes of cobbles in steel rolling using conditional probability. Kushal *et al.* [14] identified wear and tear as one of the causes of cobble, but did not specify the forms of wear and tear. This paper is focused on identifying the specific forms of wear (such roll wear and die wear) as causes of cobble in steel rolling. Kushal *et al.* also identified old drives as causes of cobble but did not state the conditions of the old drives that will result in cobble. Therefore, in this study, misalignment (or alignment error) was suspected as possible cause of cobble. Furthermore, this study was designed to use Chi-square to investigate the association between the defects and cobble occurrence at (P = 0.05) significant level of.

MATERIALS AND METHODS

The main material used in this study is mild steel billets from three steel rolling mills in Nigeria. The billets were all produced in Nigeria by steel scrap recycling. Each billet was targeted to have dimensions of 100mm×100mm×6m. However, little cross-sectional differences were observed in the billets, which resulted in differences in rhombodity. Methods adopted for this study is illustrated in Figure 6.

The equipment used for this study includes:

i. **Measuring Tape (25ft):** The tape was used to measure the lengths of the billets.
ii. **Mitutoyo 500 -196 -30 Digital Calipers**: This equipment was used to measure the cross-sectional dimensions of the billets.
iii. **Optical Gauge:** Roll alignment defects were detected detected using this equipment.
iv. **Venier Calipers**: This equipment was used to measure roll radius
v. **Odd leg Calipers**: This equipment was used to measure the die-entrance diameters in the mill train.
vi. **X100 Magnifying Glass**: This equipment was used to detect cracks on rolls.

Sources of research information used for this study includes: internet, textbooks and the production records of the various rolling mills visited for the study. In order to determine the possible causes of cobble in steel rolling, three steel rolling mills in Nigeria, tagged A, B and C were visited at different occasions to inspect the mill train of each plant and observe rolling operations leading to cobble incidence. Mill A is located at Odogunyan Ikorodu in Lagos Stale; Mill B, is located at Ogijo Ogun State and Mill C, is located at Aladja Delta State.

The methods adopted for this study are described as follows:

1. **Inspection of mill train:** At this point, conditions of the mill train were thoroughly inspected to see if there is mechanical fault on the mill train. During the inspection, the cross-sectional dimensions of the test rolled billets were measured and were used to calculate the average rhombodity for each mill.
2. **Mill Maintenance (Before Test Rolling)**: At this stage, the necessary corrections were made on the mill train if any fault was detected. Thorough maintenance was done to ensure that the mill train is in good working condition.
3. **Test-Rolling:** Having ascertained that the mill train is in good working conditions, Test-Rolling was conducted to observe cobble occurrence. Once there is cobble incidence, the rolling operation was stopped momentarily and the cobble was carefully removed and the mill train was again inspected. The defects observed were recorded accordingly.
4. **Data collection:** At this stage, the relevant qualitative and quantitative data were collected. The data includes the types of defects detected within the limit of inspection, number of times each defect appears (frequency) for each cobble incidence. For this study, inspection was limited to ten rolls closest to the point of cobble occurrence as shown in Figure 5.
5. **Data Analysis:** Having the collected the relevant data, result calculations and statistical analysis were done. Chi-square test was conducted using Microsoft Excel (version 2010).
6. **Result Presentation:** Finally, the results obtained were presented in tables and bar charts.

The defects were detected as follows:

1. **Worn-out rolls:** During the test rolling Worn out rolls were detected on the mill train by visual inspection. First, the roll must have polished appearance and when touched the smoothness is felt. However, an experience staff in rolling department has to decide whether the roll should be categorized as worn-out or not. Visual inspection has been adopted in a similar study [31].
2. **Cracked rolls:** The cracks on rolls were detected by visual inspection aided by x100 magnifying glass. During inspection, the magnifying glass was kept at a distance of about 3cm from the roll surface suspected to have crack. The glass magnifies the crack for proper vision if there is any.
3. **Distorted rolls**: Distorted roll were detected by measuring roll diameter and width using venier calipers at different points on the roll. Difference in roll width or roll diameter is an indication that the roll is distorted.
4. **Die blockage**: Die blockage was detected by carefully measuring the die entrance diameter at different points on the die using odd leg calipers. Die was categorized as blocked, if at any point the diameter is less than the normal.

5. **Worn-out dies**: worn-out dies were detected in a similar way with die blockage, but die is classified as worn-out if at any point the die entrance diameter is more than normal.
6. **Roll misalignment:** Roll misalignment was detected using optical alignment gauge.

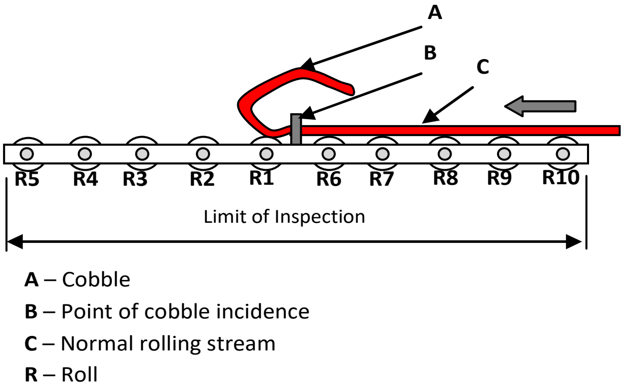

Figure 5. Schematic diagram showing the limit of inspection

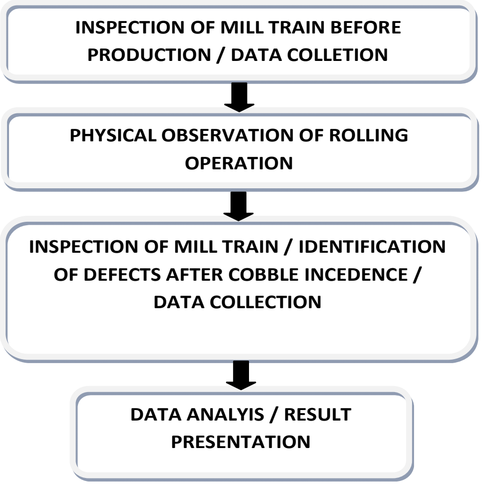

Figure 6. Research methods

Billet Parameters

1. Billet rhombodity was calculated using Eq. (13).

$$R_b = 2\left(\frac{d_2 - d_1}{(d_1 + d_2)}\right) \times 100\% \qquad (13)$$

where R_b is the rhombodity d_1 and d_2 are the cross-sectional diagonals of the billet.

2. Cobble rate was calculated using Eq. (14).

$$C_R = \frac{N_C}{N_R} \times 100\ \% \qquad (14)$$

where C_R is cobble rate, N_C is the number of cobbled billets and N_R is the total number of rolled billets.

Modeling of the probability index

In this study, cobble occurrence was associated with a number of defects frequently observed on the mill train each time cobble occurs. The model was developed based on the concept of conditional probability. The rule states that if A, and B are two dependent events, the probability of the two event occurring dependently is given by Eq. (15) [32].

$$P(A \cap B) = P(A) * P(B/A) \qquad (15)$$

where $P(A \cap B)$ is the probability of events A and B occurring dependently, $P(A)$ is the probability of event A occurring and $P(B/A)$ is the probability of B occurring, given that A has occurred.

Therefore, from Eq. (19), the probability of cobble formation due to a defect *di* is given by Eq. (16).

$$P(di \cap c) = P(di) * P(c/di) \qquad (16)$$

where $P(di \cap c)$ is the probability of defect *di* and cobble c occurring dependently, $P(di)$ is the probability of defect *di* occurring in the mill train and $P(c/di)$ is the probability of cobble occurrence due to defect *di*.

Given that

$$P(di) = \overline{F}(di)\frac{N_{di}}{\sum_{i=1}^{i=k} N_{di}} \qquad (17)$$

$$P(c/di) = \frac{N_C}{N_R} \qquad (18)$$

$$F(di)_j = \frac{\sum (f(di)/n)_j}{N_{di}} \qquad (19)$$

$$\overline{F}(di) = \frac{1}{N}\sum_{j=1}^{j=N} F(di)_j$$

$$= \frac{1}{N}(F(di)_1 + F(di)_2 + F(di)_3) + \ldots F(di)_N) \qquad (20)$$

where N_C is the number of cobbled billets and N_R is the number of work piece (billets or ingot) rolled. The term $f(di)$ of Eq.(19) is the frequency of occurrence of the defect *di* within the limit of inspection. The term *n* is the number of rolls closest to the origin of the cobble referred to as limit of inspection in this study. N_{di} is the total number of occurrence of defect *di* within the limit of inspection. $F(di)$, given by Eq. (19) is the occurrence factor of the defect *di* for analysis of one rolling mill, while $\overline{F(di)}$, given by Eq. (20) is the average occurrence factor of the defect *di* for more than one rolling mill. Defect occurrence factor in this study refers to the number of times the defect occurred within the limit of inspection for a given number of cobble cases. It should be noted that one defect, say die blockage can occur at several points on the mill train for a cobble incidence. *N* is the number of rolling mills sampled in the study. The terms, *i* and *j* are whole positive integer, such that $i = 1, 2, 3, \ldots k$ and $j = 1, 2, 3, \ldots N$, where k is the number of the various defects detected within the limit of inspection and *N* is the number of rolling mills sampled in the study.

The probability of cobble due to the occurrence of defect *di* , in a rolling, *j* is given by Eq. (21).

$$P(di \cap c)_j = F(di)_j \frac{N_c N_{di}}{N_R \sum_{i=1}^{i=k} N_{di}} \qquad (21)$$

To obtain the probability index, Eq. (21) was multiplied by 100 [33]. Thus, the probability index is given by Eq. (22).

$$PI(di)_j = F(di)_j \cdot \frac{N_c N_{di}}{N_R \sum_{i=1}^{i=k} N_{di}} \times 100 \qquad (22)$$

The probability index of the defect, *di* for more than one rolling mill, say Mill1, Mill 2, Mill 3,…Mill N put together is given by Eq. (23).

$$PI(di) = \overline{F}(di) \frac{\sum_{j=1}^{j=N} N_{Cj} \sum_{j=1}^{j=N} N_{dij}}{T_{Nd} \sum_{j=1}^{j=N} N_{Rj}} \times 100 \qquad (23)$$

Where

$$\sum_{j=1}^{j=N} N_{Cj} = N_{C1} + N_{C2} + N_{C3} + \dots\ N_{CN} \qquad (24)$$

$$\sum_{j=1}^{j=N} N_{dij} = N_{di1} + N_{di2} + N_{di3} + \dots\ N_{diN} \qquad (25)$$

$$\sum_{j=1}^{j=N} N_{Rj} = N_{R1} + N_{R2} + N_{R3} + \dots\ N_{RN} \qquad (26)$$

$$T_{Nd} = \sum_{j=1}^{j=N} \sum_{i=1}^{i=k} N_{dij} = \sum_{i=1}^{i=k} N_{di1} + \sum_{i=1}^{i=k} N_{di2} + \sum_{i=1}^{i=k} N_{di3} + \dots \sum_{i=1}^{i=k} N_{diN} \qquad (28)$$

The rolling mills sampled in this study were tagged A, B, and C. Therefore, MillA, Mill B, and Mill C stand for Mill1, Mill 2, and Mill 3 respectively. Thus,

$N_{C1} = N_{CA}$ = Number of cobble incidence in mill A
$N_{C2} = N_{CB}$ = Number of cobble incidence in mill B
$N_{C3} = N_{CC}$ = Number of cobble incidence in mill C
$N_{R1} = N_{RA}$ = Number of rolled billets in mill A
$N_{R2} = N_{RB}$ = Number of rolled billets in mill B
$N_{R3} = N_{RC}$ = Number of rolled billets in Mill C
$N_{di1} = N_{diA}$ = Number of defect, *di*, detected in Mill A
$N_{diB} = N_{diB}$ = Number of defect, *di*, detected in Mill B
$N_{diC} = N_{diC}$ = Number of defect, *di*, detected in Mill C

Note: T_{Nd} is the total number of occurrence of all the defects detected within the limit of inspection and for all the rolling mills sampled in the study. Although the value of n is taken based on the discretion of the researcher, but as a statistical approach, the larger the sample size (i.e. limit of inspection), the more the accuracy of the results. Suppose *di* stands for cracked roll, N_{di} is then the number of cracked rolls detected within the limit of inspection. Also, if cracked rolls, worn out rolls and die blockage were detected within the limit of inspection, then T_{Nd} is the total number of occurrence of both cracked rolls, worn out rolls and die blockage detected within the limit of inspection in all the mills sampled in the study. If three defects, say cracked rolls, die blockage, and worn out rolls were detected in a mill inspection, then, $k = 3$. ∑ is summation notation. For results of the analysis done with the proposed model to be accepted, the following conditions must be met.

1. $0 < PI(di) \leq 100$
2. $0 < F(di) \leq 1$

Conditions 1 and 2 imply that the defect *(di)* is a potential cause of cobble. On the other hand, zero probability index (i.e. $PI(di) = 0$) indicates that defect *(di)* is not associated with cobbles occurrence.

Advantages of the proposed model

The advantages of the proposed model over the methods stated in previous studies are given as follows:

1. The probably model proposed in this paper is a quick approach to predicting the causes of cobble in steel rolling operations.
2. Visual inspection, which is adopted in this study for detection of cobble causing defects, does not require much skill.
3. Cobble causing defects are investigated within a specified limit referred to as limit of inspection.

Limitations of the proposed model

The limitations of the model proposed in this paper are stated as follows:

1. The proposed model cannot be used to detect cobble causes outside the limit of inspection.
2. Only a few mechanical faults can be detected by visual inspection adopted in this study.
3. Other potential causes of cobble, such as high voltage and electronic failure [14] cannot be detected by visual inspection.
4. Metallurgical factors, such as temperature of the workpiece, which is noted as potential cobble causes [27] were not considered in the proposed model.

Result calculations

Worn-out rolls in Mill A (See Table 2)

From Table 2, it is given that within the period of study, Mill A recorded 14 cobble cases. Immediately after the first case, 7 worn out rolls were observed out of the 10 rolls closest to the origin of the cobble, which gave frequency of 7 out of 10 rolls, i.e. (7/10). In a similar manner, (5/10), (3/10) (4/10), (1/10), (7/10), (2/10), (3/10) and (7/10) were recorded respectively for cases 2, 3, 5, 6, 7, 10 11 and 13. The total number of worn out rolls recorded for Mill A was 9. Table 5 shows the probability indexes of all the defects detected in this study, which was calculated as follows:

$$i = 1, j = A$$

$$\sum (f(d1)/n)_A = (33/10) = 3.3$$

$$N_{d1A} = 9$$

$$F(d1)_A = \frac{\sum (f(d1)/n)_A}{N_{d1A}} \approx 0.3667 \qquad \text{(See Table 5)}$$

Worn out rolls in Mill B (See Table 3)

$$i = 1, j = B$$

$$\sum (f(d1)/n)_B = (21/10) = 2.1$$

$$N_{d1B} = 7$$

$$F(d1)_B = \frac{\sum (f(d1)/n)_B}{N_{d1B}} \approx 0.3000$$

(See Table 5)

Worn out rolls in Mill C (See Table 4)

$$i = 1, j = C$$

$$\sum (f(d1)/n)_C = (38/10) = 3.8$$

$$N_{d1C} = 11$$

$$F(d1)_C = \frac{\sum (f(d1)/n)_C}{N_{d1C}} \approx 0.3455$$

(See Table 5)

Mill A, MillB, and MillC put together

$$\therefore N = 3$$

$$\overline{F}(d1) = \frac{1}{3}\sum_{j=1}^{j=3} F(d1)_j = \overline{F}(d1)_{ABC}$$

$$= \frac{1}{3}(F(d1)_1 + F(d1)_2 + F(d1)_3)$$

$$\equiv \frac{1}{3}(F(d1)_A + F(d1)_B + F(d1)_C)$$

$$= \frac{1}{3}(0.3667 + 0.3000 + 0.3455)$$

$$\approx 0.3374 \qquad \text{(See Table 5)}$$

$$\sum_{j=1}^{j=3} N_{Cj} = N_{C1} + N_{C2} + N_{C3}$$

$$\equiv N_{CA} + N_{CB} + N_{CC} = 14 + 9 + 12 = 35$$

$$\sum_{j=1}^{j=3} N_{d1j} = N_{d11} + N_{d12} + N_{d13}$$

$$\equiv N_{d1A} + N_{d1B} + N_{d1C}$$

$$= 9 + 7 + 11 = 27$$

Using Eq. (26), the probability index of worn out rolls for the individual mills was calculated as follows:

Mill A

$$PI(d1)_A = \frac{0.3667 \times 14 \times 9}{280 \times 33} \times 100 \approx 0.5000 \quad \text{(See Table 5)}$$

Mill B

$$PI(d1)_B = \frac{0.3000 \times 9 \times 7}{225 \times 34} \times 100 \approx 0.3843 \quad \text{(See Table 5)}$$

Mill C

$$PI(d1)_C = \frac{0.3455 \times 12 \times 11}{267 \times 45} \times 100 \approx 0.3796 \quad \text{(See Table 5)}$$

Mill A, MillB, and Mill C put together

Using Eq. (27), the probability index of worn out rolls for mills A, B and C put together was calculated as follows

$$PI(d1)_{ABC} = \frac{0.3374 \times 35 \times 27}{772 \times 112} \times 100 \approx 0..3688$$

(See Table 5)

RESULTS AND DISCUSSION

The results of this study include probability indexes of the detected defects and average cobble rates for the individual mills and for both mills put together. Table 1 shows number of rolled billets, average rhombodity of the test rolled billets and the conditions of the mill train before test rolling. Table 2 shows the result of cobble incidence in Mill A; Table 3 shows the result of cobble incidence in Mill B and Table 4 shows the result of cobble incidence in Mill C. The test rolling results given in Table 2, Table 3 and Table 4 were summarized in Table 5. The content of Table 5 includes average cobble occurrence factor, $\overline{F}(di)$, number of occurrence of a particular defect, N_{di}, and probability index, $PI(di)$. Table 6 shows the result of Chi-square test of the association between mill defects and cobble occurrence. Table 7 shows the products and cobble rates of the various mills. Figure 7 and Figure 8 are graphical representations of cobble occurrence factors and probability indexes respectivel The number of rolled billets (N_R), billet rhombodity (R_b) and the conditions of Mills A, B and C before test rolling are given in Table 1, which shows that after the maintenance on the mill train prior to test rolling, no defect was detected in any of the mills. This suggests that the mills were all in good condition before the test rolling. The numbers of rolled billets (N_R) were 280, 225, and 267 for mills A, B, and C respectively. This result shows that different numbers of billets were used in mills A, B, and C for the test rolling. Furthermore, Table 1 shows average billet rhombodity (R_b) of 3.6%, 4.5%, and 3.8% respectively for mills A, B, and C. This result suggests that billet moulds of Mill A are more sound compared to those of Mill C, and the billet mould of C is better than that of Mill B.

Table 1. Number of rolled billets, billet Rhombodity and conditions of the mill train before test rolling

Rolling mill	N_R	Before Test Rolling						
		Worn out rolls	Cracked rolls	Distorted rolls	Worn out dies	Die setting	Roll alignment	Billet Rhombodity (R_b) (%)
A	280	nil	nil	nil	nil	ok	ok	3.6
B	225	nil	nil	nil	nil	ok	ok	4.2
C	267	nil	nil	nil	nil	ok	ok	3.8

Table 2. Result of Cobble Incidence in Rolling Mill A

	Detected defects and their occurrence factor					
Incidence	Worn-out rolls (d1)	Cracked Rolls (d2)	Distorted rolls (d3)	Worn-out dies (d4)	Die blockage (d5)	Roll Alignment error (d6)
Case 1	7/10	6/10	nil	nil	nil	3/10
Case 2	5/10	5/10	1/10	2/10	nil	5/10
Case 3	3/10	4/10	nil	nil	5/10	nil
Case 4	nil	nil	nil	nil	nil	7/10
Case 5	4/10	4/10	nil	nil	2/10	nil
Case 6	1/10	1/10	nil	nil	nil	nil
Case 7	7/10	7/10	nil	nil	nil	2/10
Case 8	nil	nil	nil	1/10	nil	nil
Case 9	nil	nil	1/10	nil	nil	nil
Case 10	2/10	3/10	nil	nil	3/10	nil
Case 11	3/10	3/10	nil	nil	nil	nil
Case 12	nil	nil	nil	3/10	nil	3/10
Case 13	1/10	nil	nil	nil	2/10	nil
Case 14	nil	nil	1/10	nil	nil	1/10
$\sum(f(di)/n)_A$	33/10 (3.3)	33/10 (3.3)	3/10 (0.3)	6/10 (0.6)	12/10 (1.2)	21/10 (2.1)
N_{diA}	9	8	3	3	4	6
$F(di)_A$	0.3667	0.4125	0.1000	0.2000	0.3000	0.3500

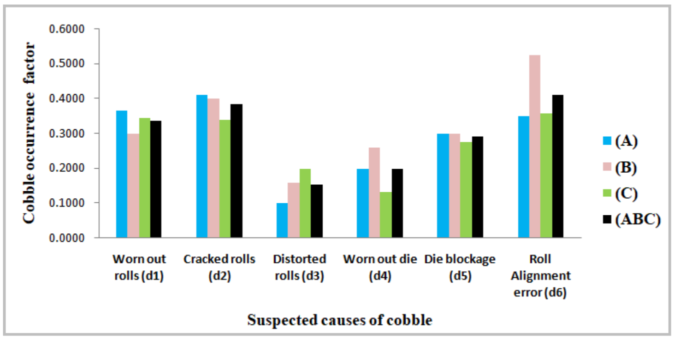

Figure 7. Plot of cobble occurrence factors of the suspected defects

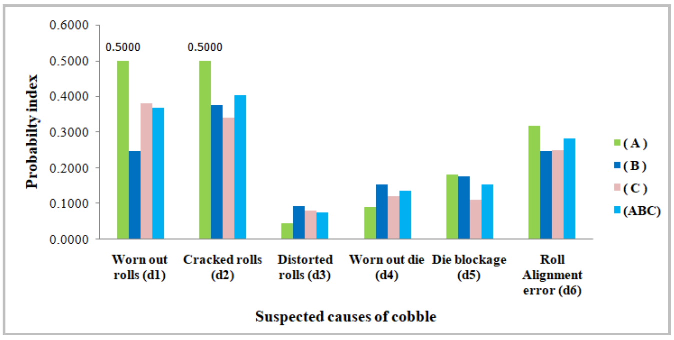

Figure 8. Plot of probability indexes of the suspected causes of cobble

However, the billet rhombodity of the both mills are less than the 5% maximum specified by American Society Testing Material (ASTM) [34]. Therefore the conditions of billet moulds in both mills are satisfactory. Table 2 shows the result of the analysis of cobble incidence in Mill A. From the table, a total of 14 cobble cases were recorded out of two hundred and eighty (280) billets test rolled. Inspection was conducted within ten rolls closest to the point of cobble occurrence, i.e. n = 10. The defects observed in Mill A include worn out rolls, cracked rolls, distorted rolls, worn out dies, die blockage, and roll alignment errors. The results given in Table 2 shows that cracked rolls occur most often in Mill A, with occurrence factor (0.4125), followed by worn out rolls with occurrence factor (0.3667). On the other hand, distorted rolls had the least occurrence factor (0.1000). It can be deduced from this result that cracking of rolls occur most frequent in Mill A, followed by wearing out rolls, while roll distortion showed least occurrence. The rapid cracking of rolls in Mill A might have resulted from mill vibration, roll misalignment, substandard roll material, and poor roll design. In addition, the frequent wearing of rolls might be a result of excessive friction between the workpiece and the rolls, caused by excessive rolling load. Kushal *et al.* [14] gave evidence to this. The result of the analysis of cobble incidence in Mill B is given in Table 3. From the table, a total of 225 billets were test rolled in Mill B. Nine cobble cases were recorded and mill inspection was also limited to ten rolls closest to the point where cobble occurred, i.e. n = 10. The defects observed after cobble incidence includes worn out rolls, cracked rolls, distorted rolls, worn out dies, die blockage, and roll alignment errors. The results in the Table shows that roll misalignment (or roll alignment error) occur most often with occurrence factor (0.5250), followed by cracked rolls with occurrence factor (0.4000) and the least was distorted rolls, with occurrence factor (0.1600). The high rate of roll misalignment in Mill B might be a result of mill vibration, use of old rolls, poor mill design, and poor operational standards.

Furthermore, Table 4 shows the results of the analysis of the cobble incidence in Mill C. The results presented in the table shows that a total of 267 billets were test rolled and out of which 12 cobble cases were recorded. As in Mills A and B, the limit of inspection was 10. The defects observed also include worn out rolls, cracked rolls, distorted rolls, worn out dies, die blockage, and roll alignment errors. For the twelve cobble cases recorded, the defects were observed for a total of 45 times. Roll alignment error showed the highest occurrence factor (0.3511), followed by cracked rolls with occurrence factor (0.3455), while the least occurrence was shown by worn out die with occurrence factor (0.1333).

Table 3. Result of Cobble Incidence in Rolling Mill B

	Detected defects and their occurrence factor					
Incidence	Worn-out rolls (d1)	Cracked Rolls (d2)	Distorted rolls (d3)	Worn-out dies (d4)	Die blockage (d5)	Roll Alignment error (d6)
Case 1	3/10	3/10	2/10	2/10	1/10	7/10
Case 2	4/10	5/10	1/10	7/10	nil	5/10
Case 3	1/10	4/10	nil	nil	5/10	Nil
Case 4	1/10	5/10	nil	2/10	6/10l	7/10
Case 5	7/10	5/10	3/10	nil	2/10	Nil
Case 6	nil	1/10	nil	1/10	1/10	Nil
Case 7	2/10	7/10	nil	nil	nil	2/10
Case 8	3/10	nil	1/10	1/10	nil	Nil
Case 9	nil	2/10	1/10	nil	nil	Nil
$\sum(f(di)/n)_B$	21/10 (2.1)	32/10 (3.2)	8/10 (0.8)	13/10 (1.3)	15/10 (1.5)	21/10 (2.1)
N_{diB}	7	8	5	5	5	4
$F(di)_B$	0.3000	0.4000	0.1600	0.2600	0.3000	0.5250

Table 4. Result of Cobble Incidence in Rolling Mill C

	Detected defects and their occurrence factor					
Incidence	Worn-out rolls (d1)	Cracked Rolls (d2)	Distorted rolls (d3)	Worn-out dies (d4)	Die blockage (d5)	Roll Alignment error (d6)
Case 1	3/10	1/10	1/10	1/10	2/10	3/10
Case 2	3/10	5/10	1/10	2/10	nil	5/10
Case 3	nil	4/10	nil	nil	5/10	Nil
Case 4	2/10	5/10l	nil	3/10	nil	7/10
Case 5	7/10	4/10	nil	1/10	2/10	4/10
Case 6	1/10	2/10	3/10	nil	nil	Nil
Case 7	4/10	4/10	nil	1/10	nil	1/10
Case 8	3/10	nil	nil	1/10	nil	Nil
Case 9	7/10	4/10	nil	1/10	2/10	4/10
Case 10	1/10	2/10	3/10	nil	nil	Nil
Case 11	4/10	3/10	nil	1/10	nil	1/10
Case 12	3/10	nil	nil	1/10	nil	Nil
$\sum(f(di)/n)_C$	38/10 (3.8)	34/10 (3.4)	8/10 (0.8)	12/10 (1.2)	11/10 (1.1)	25/10 (2.5)
N_{diC}	11	10	4	9	4	7
$F(di)_C$	0.3455	0.3400	0.2000	0.1333	0.2750	0.3571

Table 5. Probability Indexes and Variables

Variable	Defects Observed After Cobble Occurrence						Sum
	Worn-out rolls (d1)	Cracked rolls (d2)	Distorted rolls (d3)	Worn-out die (d4)	Die blockage (d5)	Roll Alignment error (d6)	
$F(di)_A$	0.3667	0.4125	0.1000	0.2000	0.3000	0.3500	-
$F(di)_B$	0.3000	0.4000	0.1600	0.2600	0.3000	0.5250	-
$F(di)_C$	0.3455	0.3400	0.2000	0.1333	0.2750	0.3571	-
$\bar{F}(di)_{ABC}$	0.3374	0.3842	0.1533	0.1978	0.2917	0.4107	-
N_{diA}	9	8	3	3	4	6	33
N_{diB}	7	8	5	5	5	4	34
N_{diC}	11	10	4	9	4	7	45
$\sum N_{di}$	27	26	12	17	13	17	112
$PI(di)_A$	0.5000	0.5000	0.0455	0.0909	0.1818	0.3182	-
$PI(di)_B$	0.2470	0.3764	0.0941	0.1529	0.1765	0.2470	-
$PI(di)_C$	0.3796	0.3396	0.0799	0.1198	0.1099	0.2497	-
$PI(di)_{ABC}$	0.3688	0.4044	0.0745	0.1361	0.1535	0.2826	-

Interestingly, roll misalignment occurred most in mills B and C, whereas cracked rolls occurred most in Mill A. This is an indication that roll misalignment is a common problem in steel rolling mills. Vibration has been identified as the root cause roll misalignment and roll cracks in rolling mills [14]. The anomalies can also be caused by lack of mill maintenance, substandard mill equipment, etc. Table 5 shows the overall result analysis of the cobble incidence in mills A, B, and C. The table shows that for mills A, B, and C put together, the roll misalignment had the highest occurrence factor (0.4107), followed by cracked rolls with occurrence factor (0.3842), while the least is distorted rolls with occurrence factor (0.1533). From these results, it can be deduced that the defect is most associated with cobble is roll misalignment while the defect that is least associated with cobble is roll distortion. The results given in Table 5 shows that the defects that will most probably cause cobble in Mill A are worn out rolls and cracked rolls, with equal probability indexes (0.5000). The next was roll miss alignment, with probability index (0.3182), while the least is distorted rolls with probability index (0.0455). This results show conformity with the defect occurrence factor given in Table 4, which presages that the higher the occurrence factor, the higher the probability index. Also, the results in Table 5 show that the defect that will most probably cause cobble in Mill B is cracked rolls, which has probability index (0.3764), followed by worn out rolls and roll alignment error with equal probability indices (0.2470). On the other hand, the defect with the least chance of causing cobble in Mill B is distorted rolls with probability index (0.0941). For Mill C, the defect with the highest chance of causing cobble is worn out rolls with probability index (0.3796), followed by cracked rolls with probability index (0.3396). The least is distorted rolls with probability index (0.0799). This result conforms to the probability index of Mill A. This result suggests that roll distortion seldom occurs in steel rolling and rarely cause cobble.

For the results of mills A, B, and C put together, cracked rolls showed the highest probability of causing cobble with probability index (0.4044), followed by worn out rolls, with probability index (0.3688), while the defect that will least probably cause cobble is roll distortion with probability index (0.0745). From these findings, it can be said that the probability of a mill defect causing cobble varies with the mills.

Table 2 shows a total of 14 cobble cases in Mill A; Table 3 shows a total of 9 cobble cases in Mill B; and Table 4 shows a total of 12 cobble cases in Mill C. For mills A, B, and C put together, a total of 35 cobble cases was recorded. Out of the 35 cases, worn out rolls occurred in 27 cases, cracked rolls occurred in 26cases, distorted rolls occurred in 12 cases, worn out dies occurred in 17 cases, die blockage occurred in 13 cases and roll alignment error occurred in 17 cases. With these quantitative data, Chi-square test was conducted at 0.05 significant level using Microsoft 2010 Excel ToolPak to evaluate the association between the observed defects and cobble. The result of the analysis is given in Table 6 which shows significant association between the defects and cobble (p = 0.0003).

Table 6. Result of Chi-Test showing the association between the defects and cobble for mills A, B and C put together

Defects	Cobble Occurrence with Defect	Cobble Occurrence without Defect	Chi - square P - value
Worn-out rolls	27	8	
Cracked rolls	26	9	
Distorted rolls	12	23	
Worn-out dies	17	18	
Die blockage	13	22	
Roll alignment error	17	18	0.0003

Table 7. Cobble Rates in the Various Rolling Mills

Mill	Work piece	Product	N_C	N_R	C_R (%)
A	Billet	Reinforcement bars	14	280	5.0
B	Billet	Reinforcement bars	9	225	4.0
C	Billet	Reinforcement bars	12	267	4.5
Average cobble rare					4.5

Table 7 shows the workpiece and product types from the test rolling, the number of cobble cases (N_C) per number of billet billets rolled (N_R) commonly known as cobble rate (C_R). Table 7 shows average cobble rates of 5%, 4%, and 4.5% for mills A, B, and C respectively and overall average of 4.5% for mills A, B, and C put together. Also, Table 7 shows that the workpiece used for this study is billet and the product is reinforcement bars. Change in workpiece will lead to differences in the results and finding because rolling mills are often designed for specific types of workpiece and product. Hence, as the results of this study can be used for comparison of cobble incidence at mills A, B, and C, the proposed model can also be used to make comparison of cobble incidence at different rolling mills. Anyanwu et al [35] has shown that rolling operation is a very important process in converting steel scrap into finished products such as bars and sheets. However, the hazards associated with steel rolling calls for adequate precautions and compliance to safety rules and regulations. This paper focused on cobble which is among the major challenges in steel rolling. In order to proffer solutions to cobble, one need to know the causes. Effort has been made in this study to determine the possible causes of cobble using proposed probability model. In this study, the parameter *PI(di)* is termed probability index because index has been defined as a dimensionless statistical tool which has a base value of 100 and used to evaluate changes in other variables [33]. In this study, *PI(di)* was obtained through conditional probability and used to predict the chance of cobble occurrence. The limit of inspection n can be taken between 10 and 20 depending on the design of the mill and the discretion of the researcher. The term, *f(di/n)* is the frequency of occurrence of a defect *di* (within the limit of inspection). For this study, each mill train was inspection within ten rolls closest to the point where cobble occurs as shown in Figure 5. Therefore, for this study, n = 10.

Figure 7 shows that for all the defects investigated, roll alignment error had the highest occurrence factor (0.5250) which was recorded in Mill B. The next is cracked roll which occurred in Mill A with occurrence factor (0.4125) while the least is distorted rolls with occurrence factor (0.1000) at Mill A. For mills A, B, and C put together, roll alignment error showed the highest occurrence with a factor (0.4107), followed by cracked rolls, which has occurrence factor (0.3842) while the least is distorted rolls, which has occurrence factor (0.1533). Interestingly, the occurrence factors of the defects for the individual mills show conformity with the occurrence factors of the both mills put together. The high occurrence rate of roll misalignment might have resulted from the vibration of mill equipment during rolling, which has been identified as the root cause of misalignment and over 50% of machine failure [36]. The low occurrence rate of roll distortion suggests that the rolls in the both mills have dimensional stability and are most likely made with tough materials.

Figure 8 shows that for all the defects investigated, worn out rolls and cracked rolls have equal and the highest probability index (0.5000), which was recorded in Mill A. The next is worn out rolls, which occurred at Mill C with probability index (0.3796), while the least is distorted rolls, which occurred in Mill A with probability index (0.0455). For the both mills put together, cracked rolls showed the highest occurrence factor (0.444), followed by worn out rolls (0.3688) and the least is distorted rolls (0.0745). Roll cracks might have resulted from the use of substandard materials for making rolls. It can also be caused by mill vibration or/and poor operational standards such as rolling with excessive rolling load, excessive working temperature, and inadequate mill maintenance. It can also be caused by metallurgical imperfections, such as inclusions, void and cavities [37]. Rolling defects such as wavy edge, zipper cracked and edge crack have been shown as potential causes of cobble [38]. One may think that the defects with relatively high occurrence factor will have higher probability of causing cobble, but comparison of the occurrence factor given in Figure 7 and the probability index given in Figure 8 shows that the most occurring defect is roll alignment error while the defect that will most probably cause cobble is cracked rolls. For mills A, B, and C considered separately, worn out rolls/cracked rolls showed the highest probability index whereas only cracked roll showed the highest probability of causing cobble for mills A, B, and C put together. This signifies that the result from individual mills is not sufficient for drawing logical conclusion for this study.

Conclusion

From the results obtained, the following conclusions have been drawn:

1. Worn out rolls, Cracked rolls, Distorted rolls, Worn out dies, Die blockage and Roll misalignment are potential causes of cobble in steel rolling.
2. Cobbles occur more frequent with worn-out rolls, followed by cracked rolls and least with distorted rolls.
3. The probability of cobble occurrence by a defect does not depend on the occurrence frequency of the defect.
4. None of the rolling mills considered was 100% defect free.
5. Condition of the mill train affects the productivity of rolling mills.
6. The more the number of mill sample in the study, the higher the accuracy of the result of the study
7. The association between the suspected defects and cobble is statistically significant.

Based on the findings of this study, there is need for improved quality of roll materials and expertise in steel rolling. To minimize cobble incidence in steel rolling, proper inspection of the mill train is required prior to the rolling operation to ascertain that the mill is in good working condition. Billet rhombodity, heat treatment time (soaking time) and heat treatment temperature should always be checked. 5s methodology is recommended in the rolling mill area for minimizing the severity of cobble accident. It is advisable to have cobble guide in the rolling system to reduce the severity of cobble accident. A further research which will feature more than three rolling mills and wider limit of inspection is recommended. A further research is recommended in which the electrical faults will be considered. Also, a further research is recommended in which other methods of inspection, such as mechanical test will be adopted.

Nomenclature

The terms used in this paper are defined as follows:

C_R	Cobble rate
di	ith Defect in the list of al detected defects
$f(di)$	Frequency of occurrence of defect di
$F(di)$	Occurrence factor of defect di (for a rolling mill)
$\overline{F}(di)$	Average occurrence factor of defect di (For more than one rolling mill put together)
k	Number of all the detected defects
n	Limit of inspection (Number of rolls closest to the point of cobble occurrence).
N	Number of rolling mills sampled in the study
	Number of cobbled billets
N_R	Number of rolled billets
N_{di}	Number of occurrence of defect di
$P(di)$	Probability of defect di causing cobble
$PI(di)$	Probability index of defect di
R_b	Billet rhombodity
T_{Nd}	Total number of occurrence of all the defects

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