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Review

Review of the Modeling Methods of Bucket Tooth Wear for Construction Machinery

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Abstract: Construction machinery, which is widely used in infrastructure construction, is growing rapidly all over the word. However, the complex working conditions of construction machinery lead to serious wear, particularly the wear of the bucket teeth on construction machinery. To control the wear procedure, it is essential to understand the wear mechanism and identify the wear form under variable working conditions. The modeling methods of bucket tooth wear with different wear mechanisms were reviewed. The modeling methods were divided into the analytical method and the numerical simulation method. The numerical simulation method included the discrete element method, finite element method, SPH method, and so on, which were used to simulate the bucket digging process and analyze the interaction between the material and bucket teeth during the working process. This enabled a force analysis of the bucket digging process and the identification of the location of maximum wear. By establishing a wear model, it is possible to better understand and address the wear problem in construction machinery. This article aims to summarize research methods concerning the wear of wear parts in construction machinery. It provides a theoretical foundation for future investigations in this area and aims to address challenges such as lengthy wear life testing, numerous interfering factors, and the difficulty of data collection pertaining to wear parts.

Keywords: bucket teeth; wear modeling; discrete element; finite element

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1. Introduction

Construction machinery is used in a wide variety of complex and diverse working conditions, from urban infrastructure projects to mining excavations. Some construction machinery even operates under special conditions, which can cause significant wear and tear [1]. As a result, the number of broken parts and annual maintenance costs continue to increase. Bucket teeth, in particular, are susceptible to wear and fracture failure due to their direct contact with materials. Therefore, resolving wear-related problems in construction machinery parts is crucial.

However, wear is not merely a material property, but also depends on the system response [2]. In response to this, Caterpillar [3] constructed a soil laboratory to assess the performance and wear of earth-moving machinery such as loaders. Komatsu, in Japan [4], partnered with Shandong University to study the mechanical properties and wear resistance of different types of bucket teeth. Their research aims to identify the factors responsible for the differing wear resistance of bucket teeth and develop new processing techniques to improve their wear resistance.

To control the wear procedure, it is essential to first understand the wear mechanism and identify the wear form under variable working conditions. The modeling methods of bucket tooth wear with different wear mechanisms are reviewed in Section 2. The modeling methods were divided into the analytical method and the numerical simulation method, which are reviewed in Sections 3 and 4, respectively. The numerical simulation method included the discrete element method, finite element method, SPH method, and so on, which were used to simulate the bucket digging process and analyze the interaction between the material and the bucket teeth during the working process. This enabled a force analysis of the bucket digging process and the identification of the location of maximum wear. Figure 1 provides a framework of this review.

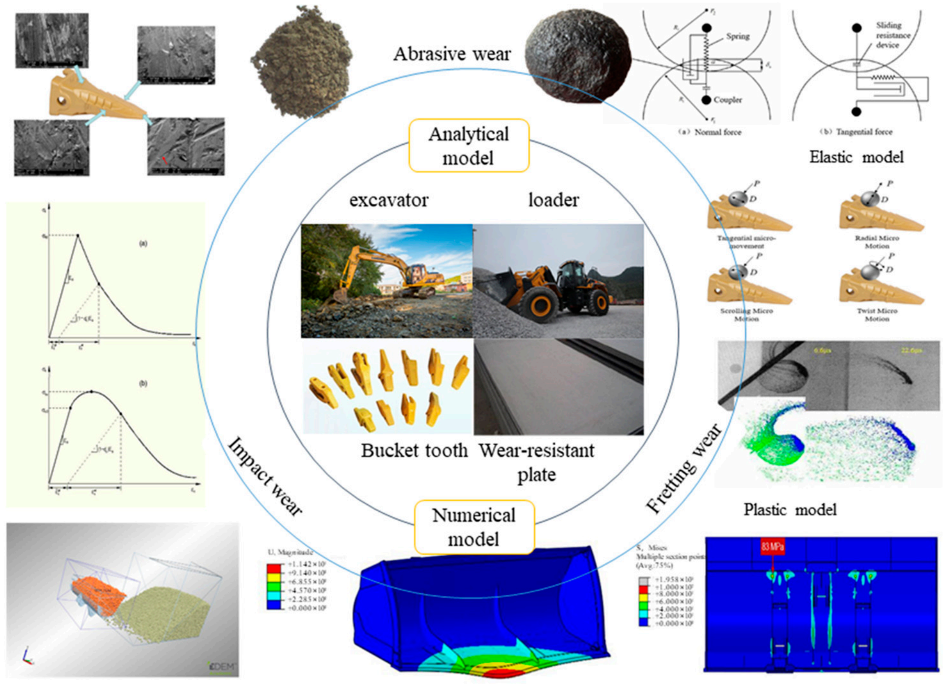

Figure 1. Framework of this review.

2. Wear Mechanism

2.1. Wear Mechanism of Bucket Teeth

There are numerous complex factors that affect the research on the wear of construction machinery's wear parts. These factors interact with each other, further complicating the issue of wear on these parts. Therefore, in order to address the wear problems associated with construction machinery's wear parts, it is crucial to first comprehend the wear mechanism and different forms of wear exhibited by various components. Jiang [5,6] et al. conducted extensive experimental studies to analyze the progression and manifestations of wear on loader pins. Their research revealed that the wear process of these pins can be primarily categorized into three stages: grinding, abrasive wear, and bonded wear. Each stage exhibits varying degrees of wear and distinct characteristics. Bucket teeth, being a vital component of construction machinery, are typically positioned at the forefront of excavator and loader buckets. These teeth come into direct contact with ores, gravel, and other materials, making them highly susceptible to significant and intricate wear. The wear of bucket teeth poses a complex challenge due to the diverse working environments and varying material contacts. Consequently, each part of the bucket teeth exhibits distinct forms of wear. After conducting an analysis, we have established the wear mechanism of each part of the bucket teeth, as illustrated in Figure 2.

The bucket teeth are a crucial component of the cantilever beam member in excavators. It comprises the shovel head, shovel seat, and ring clips, and its degree of wear and fracture directly affects the quality and efficiency of extraction. Bucket teeth come in different forms (Figure 3), including rock teeth, earth and rock square teeth, conical teeth, bucket teeth, and others [7]. The most common bucket tooth type is the conical tooth, located at the front of construction machinery, in direct contact with materials. This causes significant wear and varies in form. During excavation, the tip of the bucket teeth bear an impact load when inserted into materials, resulting in impact wear. As the bucket teeth deepen, the material above increases, causing relative sliding and two-body abrasive wear on the bucket teeth. As the bucket teeth deepen, materials roll along their surfaces into the bucket. The fine material's gravity is negligible, and pressure on the bucket teeth is minimal, causing three-body abrasive wear [8]. The unloading of the excavator and loader bucket also experience three-body abrasive wear. Fretting wear has complex sources, including environmental vibrations and alternating stresses.

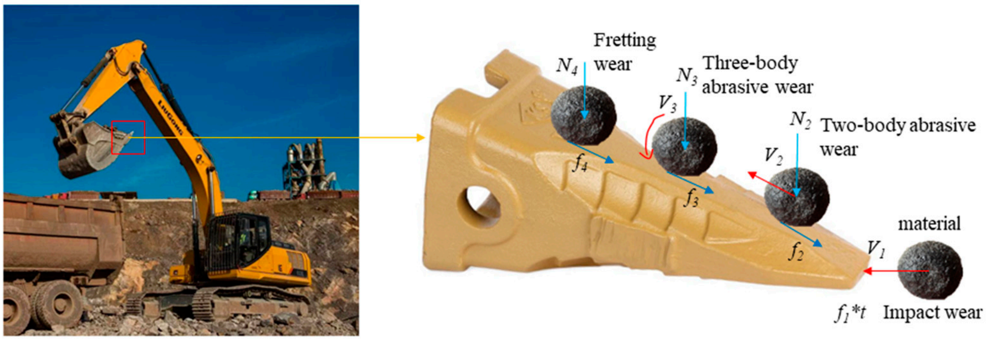

Figure 2. Tooth wear diagram of bucket.

Figure 3. Different forms of bucket teeth.

2.2. Impact Wear

Impact wear [9] is a unique type of wear that is often observed in engineering, resulting from a combination of processes such as impact and sliding friction wear. This wear type occurs on the surface of the part that keeps the abrasive material crumbling. In impact wear, concentrated compressive stress is present at the abrasive contact, the plastic rheology, and fatigue of the ductile phase on the metal surface, while the hard phase is fractured. This indicates that the stress on the material has exceeded the crushing strength of the abrasive, making it high-stress wear [10]. When inserted and excavated into a mine, bucket teeth are subjected to strong impact loads, resulting in chiseled abrasive wear. The abrasive rock grains move rapidly on the metal surface of the bucket teeth, with their sharp edges resembling knives cutting the tooth surface. This action causes plastic deformation and forms plastic change grooves. The magnitude of the cutting resistance is determined by factors such as the nature and state of the ore rock, the geometry of the cutting part, the cutting angle, and the cutting thickness [11]. Figure 4 illustrates the working environment of construction machinery engaged in excavating materials under conditions of impact wear.

Figure 4. Working conditions with impact wear governed.

Rice et al. [12] investigated the pure impact wear behavior of different impact contact subs in a dry state interface environment with different impact contact forces and different impact frequency operating conditions, as well as the punch-cut composite impact wear behavior with different tangential velocities. Engel et al. [13] investigated the composite impact wear accompanied by sliding during impact and found that there is a zero wear period during the impact wear process. This is due to the time required for the sprouting, expansion, and fracture of fatigue cracks. Yang Yi [14] investigated the impact wear behavior of Fe-Mn-Al-C lightweight high manganese steel by selecting different test conditions and setting different rotational speeds on the specimens to compare and analyze the impact wear mechanism. Zhang et al. [15] studied the wear mechanism and wear mechanism of Mn13Cr2 high manganese steel by using an impact abrasive wear testing machine and other instrumentation to simulate an actual working environment; a large number of slip bands appeared in high manganese steel after impact, and the density of slip bands increased with the increase in impact work.

2.3. Abrasive Wear

Abrasive wear is the most prevalent type of wear in construction machinery and accounts for a significant portion of overall wear. Yan [16] et al. focused on the pin set of the ZL50 series loader and conducted extensive sample observations. Through analyzing the loader pin's failure history, they determined that the primary form of wear on the pin is abrasive wear. Building upon these findings, we further examined the excavation process of construction machinery buckets and discovered that this outcome also applies to the wear experienced by bucket teeth. Throughout the entire excavation process of construction machinery, abrasive wear persists for the longest duration.

There are several approaches to classify abrasive wear. Avery [17,18] classified it into chisel wear, high stress wear, and low stress or erosion wear, based on the stresses the wear parts undergo. Burwell [19] classified it into two-body abrasive wear and three-body abrasive wear, depending on the involvement of abrasive grains during wear. Two-body abrasive wear occurs when a hard surface scratches a softer surface during frictional motion, while three-body abrasive wear happens when an abrasive grain is caught between two surfaces and causes wear on one or both surfaces. Misra and Finniel [20] further refined the classification of abrasive wear in 1980. Gates [21] concluded that abrasive wear should be classified based on the amount of stress on the wear and the form of movement of the abrasive. The evolution of the classification of abrasive wear indicates its complexity.

To analyze the wear of bucket teeth on loaders and other construction machinery, we can consider the process of shoveling materials. Typically, the bucket scoops from the bottom upwards, and the bucket teeth slowly penetrate the material, resulting in relative sliding between the two. The weight of the material exerts pressure on the bucket teeth, causing sliding friction wear, which is a type of two-body abrasive wear. When discharging, the bucket is tilted downward, and the material rolls out of the bucket (Figure 5). At this point, there is minimal contact between the material and the bucket teeth, resulting in rolling friction wear, which is a type of three-body abrasive wear.

Figure 5. Working conditions with abrasive wear governed.

2.4. Fretting Wear

In the case of the two objects mentioned above, the contact surfaces experience mutual pressure and remain stationary. However, slight periodic vibrations or alternating stress in the environment cause small reciprocal sliding between the surfaces, leading to wear or motion vice during the non-running period. Unfortunately, people are often unaware of this type of wear due to the effects of environmental vibration and alternating stress, and it is therefore often overlooked. This type of wear is commonly referred to as fretting wear.

The phenomenon of fretting was first discovered by Eden in 1911, but did not attract attention until 1927, when Tomlinson [22] designed equipment to study the process of fretting and coined the term “fretting corrosion”. With more research, the phenomenon of fatigue fretting was discovered, and it was noted that it could accelerate fatigue damage. In their study on fretting wear mechanisms, Godfrey et al. [23] found that mechanical action is the primary factor causing wear on material surfaces, while oxidation is a secondary factor. When fixed bonding surfaces experience oxidation and adhesion, an abrasive chip (a third body) forms between the contact surfaces. From a different perspective, Godet et al. [24] put forth the fretting triplet theory based on earlier research. According to this theory, adhesion, plastic deformation, surface hardening, particle exfoliation, and the formation of abrasive chips on the contact surface occur due to continuous oxidation reactions. Zhang et al. [25] studied the impact of tangential force on micro-action fatigue and discovered that wear depth increases gradually with increasing tangential force. Moreover, higher tangential force reduces micro-action fatigue life and affects the expansion of fatigue cracks. Figure 6 displays several fundamental forms of micro-motion on the bucket teeth of construction machinery.

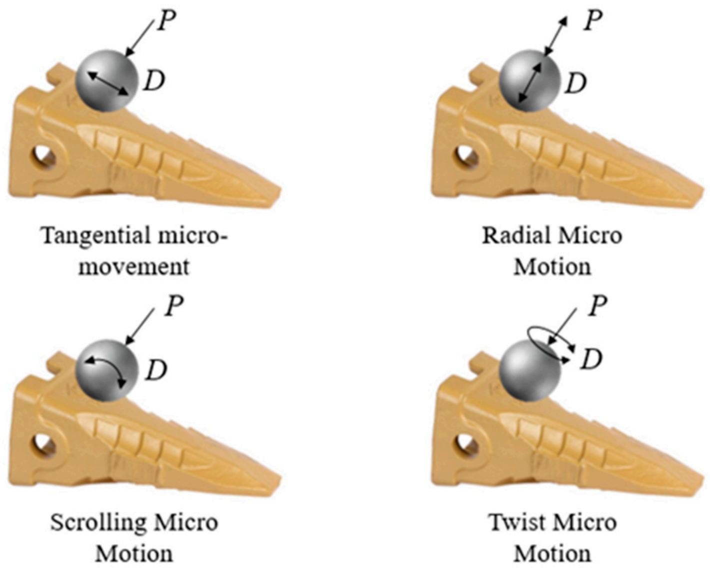

Figure 6. The basic form of micro-movement of the material on the bucket teeth [26].

Fretting wear causes plastic deformation and cracks in micro-convex bodies on friction subjoint surfaces due to contact pressure [27]. Additionally, the oxide or lubricating film on the contact surface is destroyed, leading to weld adhesion and knot formation between surfaces [28]. During fretting wear, chemical activity plays a significant role in the formation of oxide chips on the shear-off bonding points and exposed nascent surfaces. The interaction of oxygen with these surfaces leads to gradual oxidation. The generated oxide chips can cause abrasive wear and contact zone fatigue, especially due to the small amplitude, low relative velocity of sliding, and close fitting of the surface [29]. These oxide chips are not easily unloaded or dislodged from the contact area, so they act as abrasives during abrasive wear.

2.5. Wear Morphology

The surface locations of bucket teeth exhibit diverse forms of wear, leading to distinct wear profiles for each component of the bucket teeth. In the case of mining excavator bucket teeth, the majority of them exhibit high-stress wear across all surfaces. This wear is predominantly characterized by micro-cutting and plastic pear grooves, which are classified as abrasive wear and dominate the overall wear of the bucket teeth [30]. The formation of surface cracks caused by this wear leads to the accumulation of materials such as rocks on the teeth, which in turn causes Ca, O, K, Na, Si, and Al elements from sand and gravel to penetrate the bucket teeth. This process alters the original composition of the wear-resistant alloy, rendering it non-wear-resistant and resulting in a depletion or enrichment of surface alloy elements. This difference in composition between the surface and substrate of the tooling weakens its anti-wear performance, accelerates wear rate, and ultimately reduces tooling life [31].

Hu's study [32] examined the macroscopic morphology of failed bucket teeth and found that when in contact with ore, deep wear grooves and impact craters were formed on the tooth surface. A thick deformation layer was also observed on the surface of the bucket teeth, with severe plastic deformation in areas where the metal was folded on the wear surface. The wear subsurface morphology showed the appearance of a white bright layer in the deeper subsurface of the wear groove, known as the adiabatic shear layer. Although hard and corrosion resistant, this thin, brittle layer is undesirable, as it is prone to cracking and accelerates machine damage. The occurrence of the adiabatic shear layer indicates poor shear resistance of the material, making it susceptible to plastic destabilization during abrasive particle cutting or deformation. The deformation of the metal generates heat, which raises the temperature and softens the material, promoting further deformation and warming. The heat cannot be transferred to the surrounding area, leading to rapid cooling and the formation of fine martensite organization in the subsequent layer. Observations of the abrasive chip morphology showed small cutting chips. The formation of adiabatic shear layers and the generation of heat during the deformation of the metal can have a significant impact on the wear resistance of bucket teeth. By conducting further research on the material properties and design of bucket teeth, it may be possible to reduce the occurrence of adiabatic shear layers and improve the wear resistance of bucket teeth, ultimately leading to improved efficiency and reduced costs for the construction industry. In conclusion, understanding the morphology of failed bucket teeth and the factors that contribute to their wear resistance is essential for improving the efficiency of construction machinery. Further research on the material properties and design of bucket teeth is necessary for reducing the occurrence of adiabatic shear layers and improving the overall wear resistance of bucket teeth.

Valtonen et al. [30] compared the wear of a mining loader bucket's cutting edge with laboratory samples using various wear testing methods to simulate laboratory conditions. They characterized the wear surfaces and cross sections of the bucket's cutting edges and test specimens and found that work hardening occurred in all tested bucket wear steels, but the amount of plastic deformation and depth of wear varied. Valtonen et al. [33] investigated the hardness of wear-resistant steel and the impact of different abrasives on its wear rate and wear mechanism under laboratory conditions. They discovered that as the hardness of wear-resistant steel increased, the deformation of the wear surface decreased and the scratches produced by abrasive wear were most noticeable in the softer wear-resistant steel. They also found that the effect of abrasive type on the wear mechanism of wear-resistant steel was more significant than the impact of the hardness of wear-resistant steel. Thus, their study suggests that the type of abrasive is a critical factor to consider when examining the wear mechanism of wear-resistant steel. According to Keles et al. [34], bucket teeth develop a slat-martensite synthetic organization after heat treatment. Martensitic microstructure can have various forms such as slat, spiral, lenticular, and thin plates [35]. Among these morphologies, slat morphology is typically observed, as it can be easily formed through a simple heat treatment process.

3. Analytical Methods

3.1. Constitutive Model of Tooth Materials

During the operation of construction machinery such as excavators and loaders, the bucket teeth come into contact with rocks and generate a large frictional force. This force consists of normal and tangential forces. At the beginning of excavation, particles slide on the surface of the bucket teeth, causing elastic deformation. As excavation continues, stress and strain increase, leading to plastic deformation and, ultimately, fracture if the fracture strength of the tooth materials is surpassed [36].

The elastic model [37] can be divided into linear and nonlinear. The linear elastic model requires the same stress–strain curve when loading and unloading the wear-resistant material, which is rarely found in the complex working environment of construction machinery. Therefore, most of the research is focused on the nonlinear elastic model. The discrete element method can be divided into two types based on the contact methods: hard particle contact and soft particle contact. It is essentially an elastic-plastic analysis model of granular solids under quasi-static conditions in contact mechanics.

The plasticity model [38] describes a material's ability to continue deforming without immediate fracture when subjected to stress beyond its yield point. When the external force is removed, some permanent deformation remains. The conventional plasticity model's yield function depends on the stress tensor component [39]. If the value of the yield function is less than the yield stress, the deformation is elastic. If the value of the yield function is equal to the yield stress, the material's state of deformation, whether plastic or elastic, is determined by the rate of change of the yield function. The Von Mises yield function [40] is the simplest and can be expressed as follows:

$$f = \overline{\sigma} - \sigma_y \tag{1}$$

where $\overline{\sigma}$ is the yield function and σ_y is the yield stress.

The failure of wear-resistant materials is directly [41] linked to the stresses they undergo, but predicting the failure of bucket teeth is complicated due to the complex nature of construction machinery's working environment. Hence, a reliable failure model is necessary to accurately forecast the failure of bucket teeth. While there are numerous failure phenomena and forms, statistical data, both domestic and international, suggest that fatigue damage is responsible for a significant percentage (50% to 90%) of damage to mechanical parts [42]. Fracture failure models can be categorized into two groups: coupled and uncoupled methods. The coupled approach considers the coupling of plastic deformation and fracture failure, with the Gurson model being the most widely used. This model accounts for the influence of microscopic pores on plastic deformation and fracture failure, providing a better description of materials containing pores. However, the Gurson model [43] requires numerous data parameters, increasing its complexity. In contrast, the uncoupled method is simpler in form and easier to use, making it a popular choice in engineering. Uncoupled methods consider plastic deformation and fracture failure separately, and combine them using mathematical models such as elastic-plastic fracture mechanics, micro-damage mechanics, and progressive damage mechanics.

However, ultimate stresses close to or above the yield stress of the bucket teeth material are rarely generated [44]. The researchers concluded that bucket fractures are caused by long-term fatigue and that the form, arrangement, and material selection of bucket teeth can influence their failure [45]. Das et al. performed fatigue analysis of the bucket teeth on pulling shovels using finite element analysis to determine failure areas [46]. They selected a specific bucket tooth and created a three-dimensional model, which was analyzed using ANSYS software to obtain stress distribution. Static and fatigue analyses were conducted under different loads to determine the maximum stress and deformation locations, minimum safety factor, and tool life.

In actual working conditions, bucket teeth are subjected to high impact loads when in contact with ore. This generates a significant impact force that can cause plastic deformation at the tip of the tooth, leading to the formation of a plastic deformation furrow. If the yield strength of the bucket teeth material is low, this deformation can occur more easily. However, the process of plastic deformation under impact loading is a fast kinetic process, and stress changes abruptly throughout the process. Further research is needed to understand this process more fully. It is noteworthy that the proposed constitutive model offers a theoretical foundation for investigating the wear mechanism of the bucket teeth. To this end, the discrete element and finite element methods were employed to develop the corresponding model, and the wear indicators of the bucket teeth were analyzed to further investigate the wear behavior of the bucket teeth.

3.2. Friction Model

Friction models [47] can be divided into two categories: static friction models [48] and dynamic friction models [49]. Static friction models describe the friction force as a function of the relative velocity of the two objects at the interface. From a mechanical perspective, the static friction model is flexible in both normal and tangential contact. Dynamic friction models, on the other hand, describe the friction force as a function of the relative velocity and displacement of the two objects, allowing for the description of both static and dynamic characteristics of friction. As a result, dynamic friction models can provide a more comprehensive understanding of the friction state at the interface of two objects.

The Coulomb model's friction force [50] varies with normal load but is inversely proportional to the direction of motion between two objects, and remains constant regardless of their change in velocity. While an early model for describing friction, the Coulomb friction model is limited in scope, as it only accounts for the friction force between two objects when their motion velocity is greater than zero. If the velocity of two objects is zero, the Coulomb model cannot accurately predict the friction force.

The classical Coulomb friction model is one of the most widely used friction models [51], i.e., the friction force is proportional to the positive pressure on the contact surface, and its mathematical expression is

$$T = \mu P_n \tag{2}$$

or

$$\tau = \mu\sigma \tag{3}$$

In the formula, T is friction, τ is frictional shear stress, σ is positive compressive stress on the contact surface, and μ is friction coefficient

This model is applicable to the study of wear of bucket teeth, which are subjected to pressure from above when in contact with the material, while the friction generated by the material on the bucket teeth can be decomposed into tangential and normal forces.

Chen and Kobayashi [52] introduced the relative sliding velocity, a key factor affecting the friction coefficient, on the basis of the Coulomb friction condition, and proposed modifying the classical friction model by using the light smooth function-arbitrary function; the modified friction model is

$$\tau = -mk\left\{\frac{2}{\pi}\arctan\left(\frac{|u_r|}{u_r}\right)\right\}\frac{u_r}{|u_r|} \tag{4}$$

In the formula, u_r is relative slip speed and u_0 is an arbitrary constant less than u_r.

Da Vinci [53] conducted experiments in the 16th century that validated the positive correlation between frictional force and normal load, as well as the inverse relationship between frictional force and direction of motion, regardless of contact area. This theory was subsequently examined more closely, leading to the development of the Coulomb model—the first model of friction [54]. Note that the value of the friction force may be altered to some extent if the velocity is zero.

Stembalski et al. [55] proposed a method to determine the variation in the friction coefficient with sliding velocity and normal pressure for frictional subsets of different materials in friction dampers. Figueiredo and Ramalho et al. [56] addressed the problem of sheet forming affected by frictional behavior during the deformation of metal sheets on tools. In the contact region, the processed material flows over the tool surface, so all models used to study the forming process must include a methodological phenomenon that takes into account the contact with friction.

The friction models can help in understanding the wear mechanism of construction machinery, where the static and dynamic models correspond to two-body and three-body abrasive wear in bucket teeth, respectively. By using these models, the wear process and behavior of construction machinery can be better analyzed and predicted.

3.3. Wear Model

The Relative Wear model [57] was designed to simulate the positive and tangential wear caused by abrasive materials on equipment in high-impact areas. It utilizes the relative velocity and interaction forces between the bulk material and the equipment to provide the user with data that demonstrate where wear is likely to occur. However, while the model can record collision energy and the magnitude of collision force, it cannot provide an accurate value of wear. The model measures wear magnitude using four metrics: forward cumulative contact energy, tangential cumulative contact energy, forward cumulative contact force, and tangential cumulative contact force. These metrics are used to measure the energy and force magnitude when the particle and geometry collide in the forward direction and when the particles slide tangentially along the geometry.

Positive cumulative contact energy:

$$E_n = \sum |F_n v_n \delta_n| \tag{5}$$

Tangential accumulated energy:

$$E_{\rm t} = \sum |F_t v_t \delta_t| \tag{6}$$

Positive cumulative contact force:

$$F_{\rm nc} = \sum |F_n| \tag{7}$$

Tangential cumulative contact force:

$$F_{\rm tc} = \sum |F_t| \tag{8}$$

where v_n represents the forward relative velocity, v_t represents the tangential relative velocity, and δ_t represents the time step. It is important to note that the magnitude of the tangential cumulative contact force is inversely proportional to the time step, meaning that as the time step increases, the value of the tangential cumulative contact force decreases.

The Hertz–Mindlin with Archard wear model [58] extends the Hertz–Mindlin contact model to estimate the wear depth of the geometric surface based on the wear theory of J.F. Archard. This model combines Hertz's elastic contact theory with Mindlin's contact force model, which is applicable to contact phenomena at the microscopic scale. This combined model can effectively describe the contact behavior between two solid surfaces. According to this theory, the bulk material removal volume is proportional to the frictional work performed by the particles as they move through the material's surface. This model considers both the elastic deformation and the plastic deformation of the contact interface, and uses the Hertz–Mindlin contact model (Figure 7) to calculate the contact force and the elastic deformation of the interface.

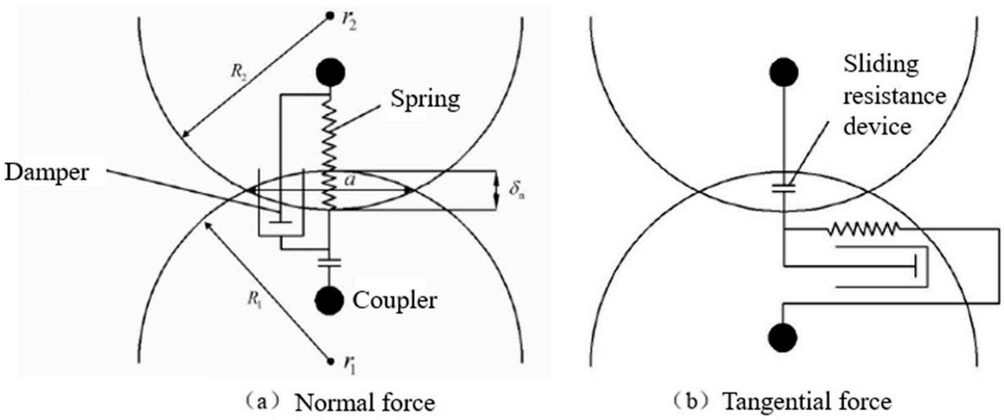

Figure 7. Hertz–Mindlin contact model.

The wear depth is then calculated based on the plastic deformation of the interface using the Archard wear law, which relates the wear depth to the frictional work performed and the material properties. It can be utilized to analyze and predict the mechanical behavior and surface deformation that occur during contact.

$$Q = WF_n d_t \tag{9}$$

where Q is the volume of material removed, d_t is the wear range, and W is the wear constant.

$$W = \frac{K}{H} \tag{10}$$

where K is the wear coefficient and H is the hardness of the material being ground. The W value is what is entered in the EDEM software. This simplifies the input of parameters in EDEM, as the equation predicts the volume of the material to be removed, which is rearranged in EDEM to give each cell a depth of

$$h = \frac{Q}{A} \tag{11}$$

where A is the area of the removed material.

The Hertz–Mindlin with Archard wear model takes into account the contact between the rock and the bucket, as well as the contact between particles within the rock, to predict the areas where wear is most likely to occur during excavation. Additionally, it provides an estimate for the depth of wear based on the material properties of the rock and the bucket. This information can be used to optimize the design of construction machinery and to develop more effective wear-resistant materials.

4. Numerical Simulation Methods

4.1. Introduction to Numerical Modeling Methods

Discrete element method (DEM), finite element method (FEM), and Smoothed Particle Hydrodynamics (SPH) are commonly used numerical simulation methods that find applications in studying engineering problems, including those related to buckets.

The discrete element method [59] is primarily employed for simulating particle flow and interparticle interactions. In the context of bucket applications, DEM can be utilized to simulate the movement, accumulation, and discharge of granular materials within the bucket. By conducting discrete element simulations, it becomes possible to examine the flow properties, inter-particle collisions, and friction of the granular material inside the bucket. This enables the evaluation of the bucket's operational efficiency and design parameters.

Finite element methods [60] find extensive application in structural mechanics analysis and materials simulation. In the context of bucket studies, the finite element method can be employed to simulate the structural response and stress distribution of the bucket. By discretizing the bucket geometry into a finite number of small units and considering the material properties and loading conditions, it becomes possible to calculate the deformation, stresses, and strains experienced by the bucket under operating loads. Consequently, the structural reliability and fatigue life of the bucket can be evaluated.

The SPH method [61] is a numerical simulation method based on a particle model and is primarily utilized for fluid dynamics problems. Within bucket applications, the SPH method can be employed to simulate the flow behavior of a fluid, such as water or slurry, inside the bucket. By discretizing the fluid into a series of masses and solving the equations based on the interactions between these masses and hydrodynamics, it becomes possible to obtain information such as velocity, pressure, and fluid surface shape within the bucket.

Each of these methods possesses distinct advantages and application scopes within the realm of bucket studies. However, the selection of the appropriate method also hinges upon the specific problem requirements and the simulation's complexity. In practical applications, it is common to combine multiple numerical simulation methods to comprehensively analyze and solve engineering problems related to buckets. For instance, coupling discrete elements with finite elements or finite elements with SPH can be employed. This allows for a more holistic approach to addressing bucket-related challenges. Table 1 presents a comparison of the three aforementioned methods.

Table 1. Features of discrete element, finite element, and SPH.

Algorithm	Applicable Object	Simulation Research of Bucket Teeth
DEM	Numerical simulation method for solving discontinuous media problems	The simulation of the shovel digging process can obtain the motion characteristics of the bucket and determine the maximum wear position
FEM	Numerical techniques for solving approximate solutions to boundary value problems in partial differential equations	The force of each part of the bucket teeth is simulated to determine the maximum load position
SPH	Fluid or solid	Coupled with finite element to study the material movement and study the wear of bucket teeth in natural conditions

4.2. Discrete Element Method

The discrete element method (DEM) is a numerical simulation technique that solves the problem of discontinuous media [56]. Originating from molecular dynamics, it models the medium as a collection of discrete particles with unique properties and independent motion. The particles have specific geometric, physical, and chemical characteristics, and their behavior is controlled by classical equations of motion. The motion and position of the particles describe the deformation and evolution of the entire medium. DEM is widely used in simulating material motion processes of construction machinery such as excavators and loaders.

In 1998, Takahashi [62] first conducted the first discrete element simulation of a loader bucket's loading process. They compared the extracted bucket resistance with experimental results, providing an effective method for bucket analysis and design. Coetzee [63] developed a simulation model of the bucket and studied methods for determining material microscopic parameters using experiments. They compared the simulation results of the discrete element method with those of the mass point method used for the continuous model, and revised the bucket simulation model in 2009 to control errors of the loading resistance and volume of material within 20% and 6%, respectively. Yu et al. [64] used EDEM software to conduct a discrete element simulation study on the effect of the number of bucket teeth on bucket resistance drag. Their results showed that during the insertion stage, the bucket resistance increased exponentially with the insertion depth, and the number of bucket teeth had a certain effect on the resistance. However, the number of bucket teeth had no effect on the bucket resistance during the lifting stage. Zhang et al. [58] studied the wear law of bucket teeth for the WK-75 mining excavator and conducted a simulation analysis of bucket digging along the ideal trajectory using discrete element software. Their study found that the most important wear areas were the bucket teeth area and the front wall of the bucket. They also showed that the average wear depth of the bucket teeth increased with material density, hardness, grain size, and angle sharpness. Nezami [3] studied the behavior of a simplified bucket using discrete element software. They simulated the soil geometry and trajectory of the bucket for each test and compared the effect of different material shapes and sizes on the simulation accuracy. The simulations also included the actual working conditions of the excavation operation, resulting in valuable insights.

When performing discrete element simulations, the bucket model should be simplified to minimize the computational load while maintaining accuracy. Using discrete element simulations, the contact forces between the bucket and different materials, as well as the filling of materials within the bucket during excavation, can be analyzed. This provides valuable information on the load on the bucket and the bucket's motion, offering a theoretical foundation for bucket design and the simulation of working conditions for bucket teeth in mining excavators.

4.3. Finite Element Method

The finite element method (FEM) has gained wide interest in the numerical simulation of frictional wear processes [60]. Mootaz et al. [65] utilized the finite element method to analyze the interaction between the bucket and material, considering and analyzing the dynamic effects of the material. Understanding the excavation process is a vital aspect and focus of excavator research. In a similar study, Mughal et al. [66] performed finite element analysis on various excavator bucket models with different geometric parameters, including bucket curvature, using ANSYS. They determined the stresses and strains in their models and calculated the maximum values of Von Mises stress, principal stress, factor of safety, and total deformation. Through their calculations, they identified the bucket with the lowest stress and deformation, yet the largest factor of safety, among the buckets studied. Wriggers et al. [67] investigated the force exerted on the bucket during the digging to dumping process and determined that the maximum compression force occurs at the beginning of contact with the material. They also used discrete element simulation to analyze the interaction of bulk material with the bucket during digging, lifting, and dumping operations, and found that the maximum deformation of the bucket occurs at the tip of the bucket teeth. Hao [68] analyzed the loader bucket's maximum rising and tractive forces as the maximum vertical and horizontal loads, respectively, and simulated five different working conditions using ABAQUS software. The conditions included horizontal positive load, vertical positive load, vertical bias load, horizontal vertical positive load, and horizontal vertical bias load (Figures 8–12). The static strength and deformation of the loader bucket were analyzed, and stress cloud and deformation diagrams of the bucket were obtained. These simulations provided insight into the bucket's performance under various working conditions. The analysis identifies the areas of maximum stress and predicts the potential wear locations within the bucket. This assessment establishes a theoretical foundation for predicting the bucket's fatigue life.

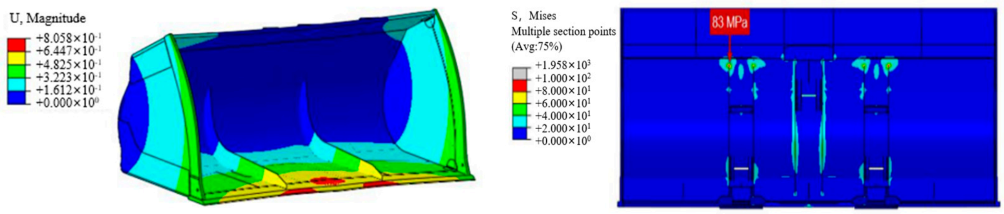

Figure 8. Stress (**left**) and pressure nephogram (**right**) under horizontal positive load conditions.

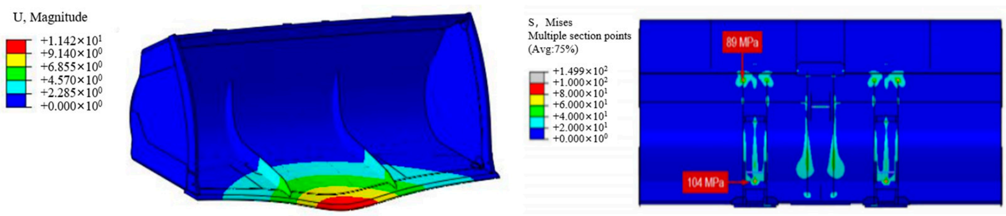

Figure 9. Stress (**left**) and pressure nephogram (**right**) under vertical positive load conditions.

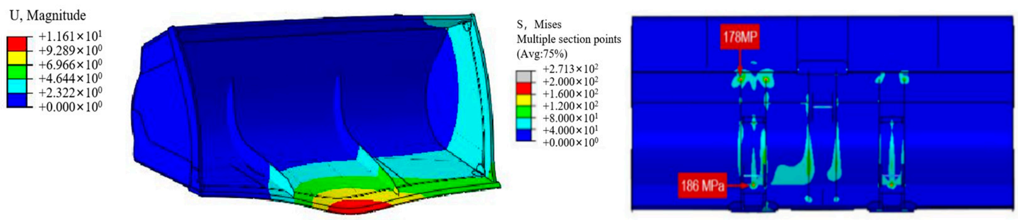

Figure 10. Stress (**left**) and pressure nephogram (**right**) under vertical off-load conditions.

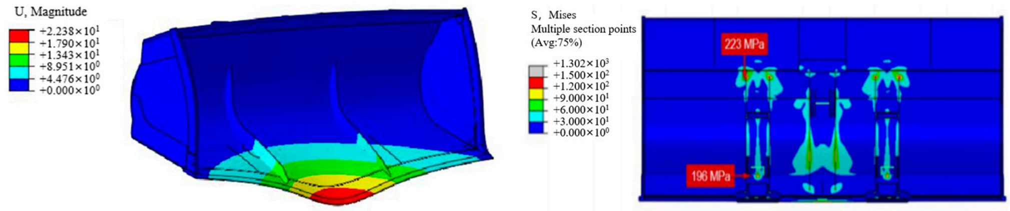

Figure 11. Stress (**left**) and pressure nephogram (**right**) under horizontal and vertical positive load conditions.

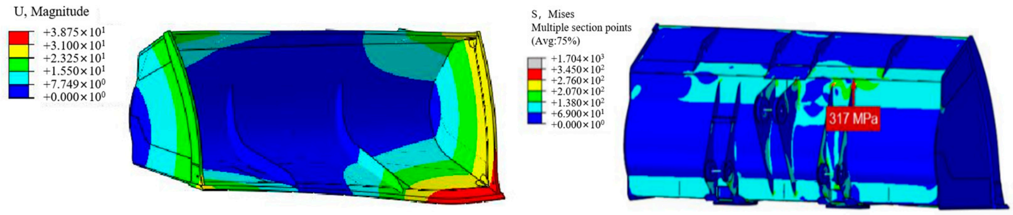

Figure 12. Stress (**left**) and pressure nephogram (**right**) under horizontal and vertical off-load conditions.

When shoveling materials, the loader bucket is inserted into the pile near the ground level, resulting in a horizontal positive load condition. The vertical positive load condition is created when the loader shovels material into the pile and then lifts the bucket. The vertical offset load condition is similar to the vertical positive load condition, except that the bucket is not centered due to the digging resistance, resulting in an offset load. The horizontal and vertical positive load condition is a combination of the horizontal positive load and vertical positive load conditions. In this condition, the loader bucket is inserted horizontally into the material pile with maximum throttle, lifted with the big arm until the rear wheels are off the ground, and simultaneously collected and dug up. The horizontal-vertical offset load condition is similar to the horizontal-vertical positive load condition, except that the bucket is not centered on the insertion and digging resistance, resulting in an offset load.

Jiang [69] et al. introduced the concept of the biased load coefficient by analyzing the loader working cycle. They proposed a novel method for calculating the forces acting on the loader. By employing reverse thinking, the calculation of the biased load condition takes precedence, considering the positive load condition as a special case. Both conditions are unified into a continuous function, and the stress changes in the movable arm from the positive load to the ultimate biased load are quantitatively analyzed using finite element software. The results reveal that the area most susceptible to damage from biased loading is the joint between the movable arm and the bucket at the bias load end. A certain degree of bias load does not significantly impact the service life and performance of the loader. However, extreme instances of biased loading should be avoided whenever possible.

Due to advances in finite element technology, it is now possible to analyze the forces on each part of the bucket and determine the maximum load on the bucket and its teeth, as well as the areas most prone to wear.

4.4. Smoothed Particle Hydrodynamics Method

The Smoothed Particle Hydrodynamics (SPH) method [61] is a meshless method that has been developed over the last two decades. The method is based on describing a continuous fluid or solid using interacting mass points, where each material point carries various physical quantities, including mass. By solving the kinetic equations of the mass group and tracking the motion trajectory of each mass, the mechanical behavior of the entire system is obtained.

Johnson [70] used a combination of the Smoothed Particle Hydrodynamics (SPH) method and the finite element method to simulate high-speed impact problems. The simulations produced results consistent with those of the experimental data, demonstrating the effectiveness of this approach. Zhong [71] developed a simulation model to investigate the interaction between a bucket and the soil, taking into account real-world conditions. Using the Smoothed Particle Hydrodynamics (SPH) algorithm, Zhong conducted numerical simulations of the bucket digging process and analyzed the resulting digging resistance and changes in gravity. The analysis demonstrated that the SPH algorithm effectively captures the dynamic behavior of the bucket digging process.

Zhang et al. [72] developed a solid model of excavator bucket teeth, which was then used to establish a soil excavation working condition model based on smooth particle fluid dynamics theory. The process of excavating different types of soil using the bucket teeth was simulated using LS-DYNA [73,74] to obtain stress changes and provide a new method for studying bucket tooth wear.

The SPH method has gained popularity due to its versatility in solving a wide range of problems. However, some limitations of the method have been identified. To overcome these limitations, the SPH method is often coupled with finite element analysis to study and analyze the research object. In the case of bucket teeth, the bucket teeth model can be established using finite element software. Using the SPH software, the material model in the working environment can be established and the SPH masses can move freely without topological relationships between them. This allows for a more realistic simulation of material motion during the bucket shoveling process.

5. Conclusions

Research on the wear and tear of construction machinery has long been a topic of interest. The working environment of construction machinery is complex, with each part subject to different levels of wear. Bucket teeth, a crucial component of construction machinery that comes into direct contact with materials, are particularly prone to wear. The wear of bucket teeth is primarily abrasive in nature, though other types of wear also occur in complex combinations. Within abrasive wear, there are two main categories based on position, force, and other factors: two-body abrasive wear and three-body abrasive wear. These different types of wear exhibit unique working conditions and wear patterns, providing valuable insight for our research on bucket tooth wear. Understanding the various forms of abrasive wear and their effects on bucket teeth is crucial for improving the durability and efficiency of construction machinery. This research has practical implications for the construction industry, as it may inform the development of new materials and technologies that can better withstand the wear and tear of the work environment.

To study the wear mechanism of bucket teeth and identify the forms and characteristics of wear at different locations, modeling is necessary. Modeling is a highly effective approach to investigate wear, as it enables the simulation of diverse operating conditions and wear mechanisms, and can predict the degree of wear of bucket teeth. The modeling approach is based on material ontology models and kinematic properties, and precise models are established for different wear mechanisms.

There are two main categories of modeling methods applied to bucket tooth wear of construction machinery, namely, analytical models and numerical models, and Table 2 summarizes the modeling methods corresponding to different wear mechanisms. This paper introduces two such models: analytical and numerical. The analytical model encompasses the intrinsic properties of the bucket tooth material, as well as models of friction and wear. By utilizing these models, researchers can gain a more comprehensive understanding of the wear and tear experienced by construction machinery components, such as bucket teeth. This knowledge can inform the development of strategies and materials to improve the durability and longevity of construction machinery. The intrinsic model of bucket tooth material includes both failure and elastoplastic models. These models are used to analyze the failure of bucket teeth based on their material properties and working conditions. By selecting appropriate friction and wear models and improving them based on the factors affecting bucket tooth wear, a highly specific model for the study of bucket tooth wear can be obtained. These models provide a theoretical basis for understanding the wear mechanisms of bucket teeth and for developing strategies to mitigate wear. The numerical model used to study bucket tooth wear is based on the discrete element, finite element, and SPH methods. By utilizing relevant software, researchers can create a simulation model of the bucket teeth and material to analyze the digging trajectory of construction machinery such as excavators and loaders. This simulation allows for an examination of the relative motion of bucket teeth and material, an analysis of the force experienced by bucket teeth, and the identification of locations where maximum stress and wear occur. Through the use of these numerical models, researchers can gain insights into the wear mechanisms of bucket teeth, which are difficult or impossible to obtain through physical experimentation alone. This research has practical implications for the development of new construction machinery materials and technologies, as well as for improving the efficiency and longevity of existing machinery.

Table 2. Modeling methods of bucket tooth wear mechanisms.

Wear Mechanisms	Working Conditions and Locations	Features	Modeling Method
Impact wear	In the case of ore excavation, the tip of the bucket tooth often occurs	With high stress, easy to destroy the surface of the material and other characteristics, more obvious wear	Failure models, wear models, finite elements, etc.
Two-body abrasive wear	In the excavator loader shoveling material, often occurs in the bucket tooth surface	Subject to certain pressure, the wear is a continuous sliding wear process, the surface of the bucket tooth is scratched, and plastic deformation occurs	Plasticity model, discrete element, finite element, SPH, etc.
Three-body abrasive wear	Often occurs on the surface of the bucket teeth during bucket discharge	Almost no pressure, wear is a continuous rolling wear process, scratches on the surface of the bucket teeth, plastic deformation	Plasticity model, discrete element, finite element, SPH, etc.
Fretting wear	Occurs throughout the bucket tooth operation and is located at the upper end of the bucket tooth	Tiny, continuous, can lead to crack propagation, highly influenced by the environment	Failure model, plasticity model, friction model

Although there are numerous mature modeling methods currently used in the study of construction machinery, many of them tend to focus on isolated factors or local phenomena, resulting in a lack of comprehensive analysis and research. Moreover, the wear tests conducted on construction machinery are often carried out under idealized conditions, neglecting the influence of various complex environmental factors. This approach typically leads to insufficient research on wear problems and deviations in research results. Additionally, due to the extended lifespan of construction machinery wear parts, many studies lack long-term observation and data accumulation, causing a mismatch between the modeling results and the actual scenario. These are the challenges that persist in current research on the wear problems of construction machinery. However, with the increasingly widespread application of construction machinery and the growing complexity of working environments, the issue of wear in construction machinery remains a focal point of research and development. The modeling method is considered a simpler, more accurate, and practical approach to studying wear in construction machinery. It continues to be an indispensable method and means for future research on the wear of construction machinery's bucket teeth.

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