A Review on the Excavator Tool Bits Wear

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***Abstract*—In recent years, application of road-headers, continuous miners and shearer has increased tremendously for the excavation purposes. The performance of these machines depends on the cutting performance and tool life of the picks used for cutting purpose, which may be conical, chisel or button shaped. The tool life of these bits is limited by its wear rate. Wear rate of individual bits depend on its design, its position and orientation on cutting drum, tool material and rock material. Wear is destruction to a surface as a result of comparative motion with respect to another object. Wear may be occurred by adhesion, abrasion, fatigue and oxidation depending on the cutting condition and environmental factors. As a general rule, it is not possible to nullify the tool wear but it could be reduced to a certain level by controlling the different factors responsible for the wear. A lot of research work, mostly experimental, pertaining to the tool bit shape and its wear has been reported in the literature since last four decades. Now a day's lot of research is going on to reduce the tool bit wear in order to enhance the excavation machine performance.**

In this paper, an attempt has been made to systematically organize the research work carried out on the cutting performance and tool wear during excavation process. Several aspects related to the performance and tool wear like tool geometry, tool material, tool installation, depth of cut and spacing, cutting forces and speed, and specific energy has been focused. The effect of water spraying on tool wear reduction and improvement on cutting performance is also included.

Keywords*—*Tool bit; continuous miner; tool wear; depth of cut; cutting force

I. INTRODUCTION

Among the available different type of tool bits, conical tool bits are mainly used in most of the excavation machines. This is due to the fact that conical bits have the advantage over the other tool bits in reducing the friction and hence the risk of ignition of combustible methane-air environment due to its protective geometry [16]. It was found that during cutting action of conical bits, its shape remained sharp due to symmetrical wear [25]. Also cutting action of conical tool bits creates compressive stress in them which gives it an edge over other tool bits due to high compressive strength for bits manufactured from brittle material and hence less chance of brittle fracture, as was observed in chisel type bit due to the occurrence of bending stress during cutting [24]. It has been observed that conical bits give better efficiency in comparison to the other tool bit shape due to the lowest specific energy for penetration [3]. The consumption of picks per cubic meter of rock excavation for conical bit was also found minimal [12].

There are different parameters on the basis of which we can measure the performance of rock cutting tools like bits shape, forces involved during rock cutting, friction between rock and tool surfaces, heat generation during rock cutting and temperature rise, rotation of bit, rock properties, water spraying effect during rock cutting, specific energy and wear produced during cutting operation. It was observed that wear of cutting tools has the following features [7];

1. Independent of rake and clearance angle of tool
2. Proportional to cut distance and width of tool
3. Inversely proportional to the depth of cut and tip hardness

Wear of rock cutting tools has been investigated on macroscopic as well as microscopic level [6, 12, 38]. After redesigning conical bit with mushroom tip, it was found that this mushroom bit has better wear resistance than conventional bit [10]. Theoretical and numerical model has also been developed by several authors based on cutting head design of machines along with cutting tool cutting performance [18, 21, 25, 40].

Based on field trials, detailed analysis on the basis of field trial has been performed on a machine used to cut the coal by taking one set of standard and another set of experimental carbide tipped conical coal bits. In order to understand the progressive nature of conical tool bits, the bits wear is divided into four wear modes. [13]. A model was developed for wear of conical bits on the basis of experimental observation and by simplifying assumptions. This model describes entire mass loss history of bit used in field trial. Mass loss history can be depicted by the following equation (1):

$$\nabla W_n = R_I t_N + R_{II}\left(t_I - t_{II}\right) + R_{III}\left(t_{II} - t_{III}\right) + R_{IV}\left(t_{II} - t_N\right) \quad (1)$$

Where ΔW_N is mass loss for Nth bit (in the order of increasing mass loss). R_I, R_{II}, R_{III} and R_{IV} are the respective wear rates in the four wear modes I, II, III and IV.

t_I= total coal mined from mode I to II

t_{II} = total coal mined from mode II to III

t_{III} = total coal mined from mode III to IV

$$t_N = \frac{N_I + N_{II} + N_{III} + N_{IV} - N}{K} \quad (2)$$

NI, NII, NIII and NIV are the number of bits in the four wear modes at the end of the field trial,

$$K = \frac{N_{II} + N_{III} + N_{IV}}{t_I} \quad (3)$$

Checkina, O.G. et al. (1996) have developed wear model for rock cutting tools on the base of analysis of worn tool profiles [21]. Wear of rock cutting tools can be described by following mechanisms [42]: (i) vibration damage, (ii) thermal fatigue as well as cracks in the tool, (iii) Impact and brittle fracture and (iv) Abrasive wear.

Wear of tools resulted in inefficient cutting, production of large debris and rapid damage of tool. Damaged and worn tool generate high forces during rock cutting than sharp tool which may result in downtime of machine component [33]. Present of large debris and methane may cause ignition. It has been found that worn pick with 15 % weight loss produces 26 % dust than new pick [25].

II. TYPE OF TOOL PICKS

The shape and geometry are important factors for efficient rock cutting as the depth of penetration and cutting force depend on it. The rock cutting bit tips are usually made by sintered powders of tungsten carbide which are brazed into the bit body made of hardened steel. A lot of experimental work has been done by researchers to measure performance of different shapes of tool bit shape. Most of the tool bits categorized under the category of point and chisel type as shown in Fig. 1. A conical bit break the rock by applying force perpendicular to its surface while a chisel bit break the rock as it moves parallel to the rock surface. Both conical and chisel bit induces tensile cracks in the rock which result in chip formation as these cracks propagate [24]. Earlier it was found experimentally that chisel types are superior in comparison to that of pointed type when cutting is done at the optimum spacing to depth ratio. On the basis of experiment following conclusions were made [1];

1. For both types of picks cutting efficiency increases to a maximum as the depth of cut is increased. Maximum cutting efficiency was achieved at a depth of 38 to 51 mm. Further increase in depth caused the decrease in cutting efficiency.
2. With increase in depth of cut or spacing between adjacent cuts resulted into increase in amount of rock removed per unit length of cut and in the coarseness of debris removed.
3. Specific energy for chisel type picks were found lower in comparison to that of pointed type at optimum spacing to depth ratio.

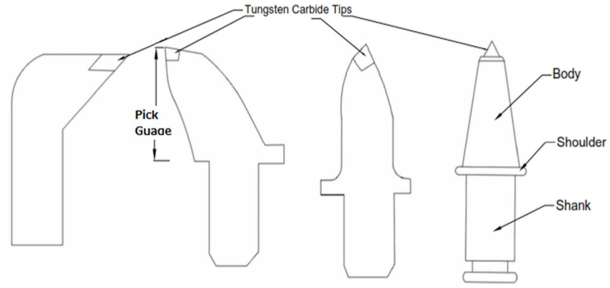


Fig. 1: Different tool picks with rectangular or round shank [5, 9, 12]

Later on conical, spherical and pyramid type bits were compared on the basis of required force for penetration, required energy to fracture the rock and stress required for chipping. It was concluded that conical type bits with an angle of 45o are superior in comparison to other two [3, 8]. The arrangements were also made for the rotation of tool bits during cutting operation and it was found that rotating point attack bits are better for hard rock cutting than radial and forward-attack bit [12].

III. AN OVERVIEW OF CONICAL TOOL PICKS

Shape and size of bit body and carbide tip are important considerations in the design of conical tool bit. Cross section area of body, tip angle and tip length depend on type of rock to be cut and manufacturers of tool bit. Tip angle (wedge angle) has significant effect on the cutting performance and wear of tool. Larger tip angle resulted in less cracks in the rock, fine grains and large energy consumption [28]. The tip angle of tool bit should be less than the half of the difference between the minimum wearing angle and the attack angle of the tool bit, and the clearance angle cannot be negative [46]. After making a detailed comparison of three different types of bits having different bit profile on the basis of forces and specific energy and it was recommended [33];

1. To use bit with longer tip also rock breaks by indentation and fracture with a penetration depth of 230 mm if bit tip is increased by a length of 230 mm.
2. If bit tip and bit body are stream lined then there would be less interaction between bit body and rock material which result in less energy consumption and less dust generation.

Bit body is designed such that it can absorb impacts of bit tip during cutting therefore bit body has more cross section area than bit tip. This cross section area of bit body may vary according to the strength of rock. Hence on the basis of design of body conical tool may be classified as follows:

1. *Tool Bit with Slender Body:* This type of bit offers better breakout and penetration but provide less strength in case of hard rocks. Hence these types of bits use for soft strength rocks.
2. *Tool Bit with Standard Body:* This type of bits arrange for a powerful combination of penetration and durability. Mostly these are used for medium strength rocks.

3. *Tool Bit with Heavy Body:* This type of bits offers greater strength and maximum durability used against hard rocks.

IV. DIFFERENT PARAMETERS AFFECTING PERFORMANCE AND WEAR OF CONICAL TOOL PICKS

Tool bit geometry, type of rock, tool bit material, Tool bit mounting configuration and tool cutting parameters (Depth of cut, tools spacing, force applied and cutting speed) play a important role in tool life and performance of excavator. Bit geometry has been described in previous section. Here other factors are described one by one.

1. Effect of rock type

One of the major differences between metal excavation and rock excavation is that in case of rock cutting tool interacts with various types of rocks and geological surroundings. In metal cutting, wear affected by chemical and thermal rather than abrasive effects. Uniaxial compressive strength, tensile rock strength, static and dynamic elasticity modulus, abrasivity and structure of rock are governing rock properties which affects to the cutter performance during rock cutting [35]. These parameters give the measure of rock cuttability for the selection of tool cutter material and excavation methods.

Rock strength act against forces applied by pick during rock cutting. As pick force exceeds the rock strength, rock is cracked. At this staged rock structure behave like a barrier to crack propagation. In the final stage as any crack reached on free surface fragmentation of rock take place. Effect of rock properties on cutting performance can be measured by variation of specific energy with rock properties. It has been found that on increasing compressive strength of rock, cutting specific energy increases [36].

Relative hardness of tip material and rock material and abrasivity of rock cause abrasive wear of rock cutting tool is main factor in wear rate of tool [23], [24]. Abrasive wear occurs by a hard protrusion on one surface or a hard particle trapped between two surfaces, which produce a groove, scratch, or indentation on a surface. If hardness of bit material is more than hardness of rock material then abrasive wear would not occur, but hardness of bit material reduces due to thermal stresses during rock cutting [41, 42]. A model was developed for tool wear along with contact condition between tool bit and rock, rock deformation and chip formation during rock cutting and shape variation of tool bit caused by wear [21]. By using this model we can optimize geometrical parameters (bit shape and rake angle). A tool with diamond hard alloy insert has been used for experiment and cutting has been performed on sand cement block to find worn tool profile. According to this model, tool shape variation caused by wear can be described by the formula:

$$\frac{\partial f_n(\varepsilon,t)}{\partial t}=K_w p(\varepsilon,t)\left[1+\left(\frac{\partial f_n(\varepsilon,t)}{\partial \varepsilon}\right)^2\right]V \qquad (4)$$

Where, $\frac{\partial f_n(\varepsilon,t)}{\partial t}$ and $p(\varepsilon,t)$ are the wear rate and contact stress in the direction to the friction surface respectively, K_w is the wear coefficient and V is velocity of cutter along x-direction.

2. Effect of tool Bit material

Tool bit wear is found to be inversely proportional to the hardness of tool tip material and body material. Tool bits are made up of two types of materials cemented tungsten carbide (for bit tip insert) and hardened steel (tool body material). Cemented tungsten Carbide (binary composition of tungsten carbide and cobalt) tips are used due to its hardness, thermal resistance, high compressive strength and high impact resistance properties. According to Indian standard IS: 5771 – 1981, grade 'T' or 'XT' of Tungsten carbide is used for mining tools [9]. The most widely used tungsten carbide is grade 'XT' type 3 with hardness range 1150-1250 HV, with 8.5-11 % cobalt content. After experimenting with the various amount of cobalt content, it was found that with the increasing cobalt percentage carbide toughness increases but hardness decreases and rapid wear of carbide tip increases with 17% of cobalt content [12]. If cobalt content is low, around 7%, then pick failure occurred due to due to fracture of carbide. It has been found that on increasing hardness of tool material bit wear resistance increases but fracture resistance decreases [17]. During microscopic study of wear of cemented carbide it was observed that grain size of tungsten carbide and content of cobalt have significant effect on composition of tungsten carbide. On decreasing the grain size of tungsten carbide hardness of cemented carbide is increased. It has been noticed that during rock cutting removal of cobalt from surface decrease the wear resistance of cemented carbide [6, 38].

3. *Effect of Tool Bit Mounting Configuration*

Conical bits are laced at cutting drum such that they can rotate about its longitudinal axis during cutting and their shanks are inclined at 35˚ to 55˚ in the cutting direction. It has been observed that rotation of bits about its axis increase their operational life. There are several bit mounting parameters that affect the wear rates and forces like attack angle, clearance angle, rake angle and tip angle as shown in Fig. 2-3 [14, 17].

It has been found that more wear takes place on flank face rather than rake face. This is due to the fact that chipping of rock occurred at rake face which offers no resistance against rake face, while rake angle and clearance angle has no effect on the removed volume of rock [17, 31].

The cutting head should be properly designed so that it can remain free from vibration during cutting operation and imposed equal jobs or forces on all picks. It has been found empirically that if cutting picks are at tilt angle of 65˚-70˚, then cutting drum may be free from vibration also have lower specific energy in this case [12, 35].

Improper design of tool and drum geometry resulted in unproductive performance, creating high noise and more dust [25]. There are the following drawbacks which affect the performance of rotary cutting drum;

1. Different depth of cut for different bits along cutting direction

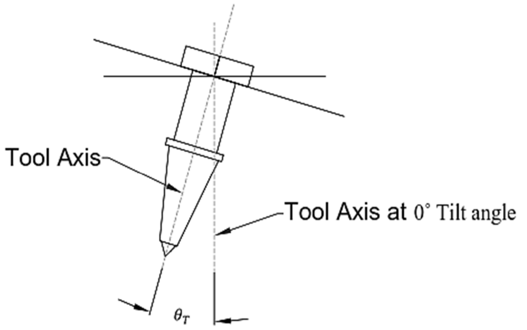


Fig. 2: Tilt angle of cutting picks [35]

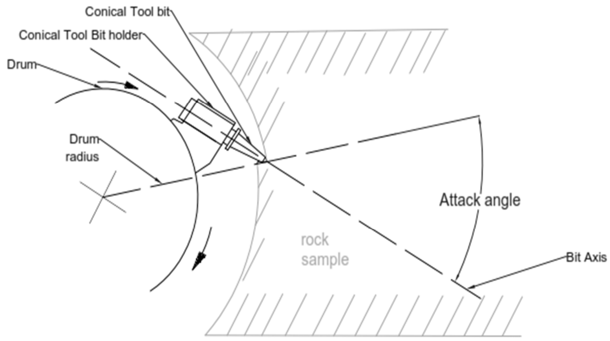


Fig. 3: Mounting of tool bit on cutting drum [8, 16]

2. More dust production
4. Excavation of material in a confined state without precut free faces

During rock cutting tool should be at an appropriate attack angle. Smaller attack angle required more normal force than larger attack angle as well as lower attack angle resulted in more friction and heat generation during rock cutting. Rise in temperature affect to the hardness of tool bit material which will result in rapid wear of tool bit [23]. It has been found that the optimum value of attack angle lies between 30˚ to 45˚ as it gives minimum area of contact between bit and rock which is necessary to produce high stress concentration in rock for the requirement of lesser force to break the rock [33]. Friction which causes ignition and thermal stress in tool bits can be decreased by a factor of three if attack angle is increased by 10˚ [12]. In an experiment at Colorado School of Mines it has been found that on increasing attack angle (48˚ to 52˚) normal force and specific energy required reduces while drag force or cutting force increases [27].

It was found that attack angle also affect the bit rotation. It has been observed that with an attack angle of 35˚ and for negative skew angle of 10˚ there will be maximum rotation of 17.5˚ of bit for each foot of cutting [14]. For conical pick the minimum cutting force was observed with an attack angle of 50˚ and clearance angle of 12˚ [35].

4. *Effect of Depth of Cut and Spacing*

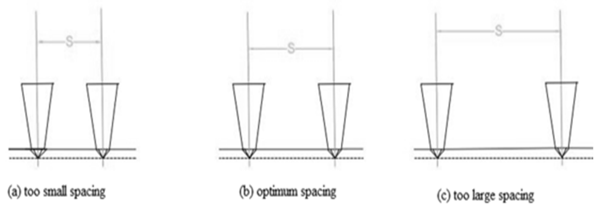
Depth of cut and spacing are important factors which affects the efficient rock cutting. It has been observed that on increasing depth of cut, thickness of the material removed during cutting and cutting force increases while specific energy and worn off material decreases [17, 25]. When spacing between the centerline of two adjacent bits, bit spacing, was increased to the optimum value the cutting efficiency increases and beyond that decrease [1, 33]. Earlier it was suggested that spacing between cutting picks should be more than three to four times of pick width [5]. Later on by performing experiment on continuous miner to understand the relation between cutting efficiency and depth of cut, it was observed that cutting efficiency improves with the increase in depth of cut per revolution and the optimum spacing was found to be twice of that of depth of cut. At optimum spacing (Fig. 4) between adjacent tool resulted into larger chip size and minimum specific energy, while due to spacing more than the optimum value, no formation of chips would occur because the tensile crack by adjacent cuts would not reach to each other and hence no formation of chips would take place and spacing less than the optimum value caused the over crushing of rock [8, 43].

5. *Effect of Force and Speed*

Forces and speed are significant factors in the measurement of bit life [20, 23]. High speed resulted in rapid wear of tool bit and worn out tool bits creates high forces during operation. The resultant force acting on a conical tool pick could be divided into three mutually perpendicular forces cutting force (FC), normal force (FN) and side force (FS) as shown in Fig. 5. The cutting force is the horizontal force and acts in the direction of rock cutting while normal force is the vertical force acting in the perpendicular direction of the cutting force. The normal force acts against the strength of the rock mass to penetrate

Fig. 4: Spacing between Conical tool bits

that rock during cutting.



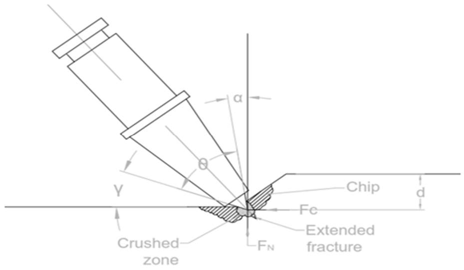


Fig. 5: Cutting action of conical pick during rock cutting

The side force is the force transverse to the cutting direction. The value of side force is very small in comparison of other two force components and usually neglected.

The cutting head of excavator should have enough power to applied load for rock cutting. Hence determination of normal force and cutting force is necessary as generation of high forces beyond the limit of machine during coal cutting may cause fracture of tool bit and failure of machine component [30, 35].

From the theory of force required to cut coal with sharp edges, the cutting force of point attack tool depends on the depth of cut, tip angle, tensile strength and compressive strength as shown in (1). It has been found that cutting force would be more in blunt edges and worn bits required four to five times more normal force and cutting force in comparison of fresh tool bits [2, 15].

$$F_c = \frac{16\pi d^2 \sigma_t^2}{\cos^2(\theta/2)\sigma_c} \tag{5}$$

Where F_c=Cutting force

d=Depth of cut

σ_t=Tensile strength

θ=Tip angle

σ_c=Compressive strength

The above relation was developed by assuming that cutting picks operates symmetrically on the cutter head of excavator along the line of advance but later on it was found that in actual practice cutting picks do not operate symmetrically. Hence the above (1) for cutting force was modified as shown in (2) [32];

$$F_c = \frac{4\pi\sigma_t d^2 \mathrm{Sin}^2\left(\frac{\alpha}{2}+\varphi\beta\right)}{\mathrm{Cos}\left(\frac{\alpha}{2}+\varphi\right)} \tag{6}$$

Here φ is friction angle between rock and tool bit.

It was observed that there are several factors which affects the normal force and cutting force like tip width and tip angle, spacing between tools, attack angle, and depth of penetration. With increase in tool tip width and tip angle, cutting force and normal force increases while for wider spacing between tools caused the decrease in normal force. The increase in attack angle caused the increase in cutting force and decrease of normal force. The increase in penetration depth caused the reduction of cutting and normal force due to occurrence of fracture and its propagation [14, 15, 27, 33, 35].

It has been observed that if the resultant force is applied in the direction of tool axis then cutting force would be the least one [46]. From the measurement of various forces acting on the coal seams, it was observed that if horizontal cut is made for coal having high ash content, bony coal, the cutting force required is three times higher than the force required for the vertical cut, while in absence of bony coal the value of cutting force is equal irrespective of coal cut made in any direction [15]. The cutting and normal force increases with the tool width and for optimum value of normal force and specific energy the chips produced are the larger one as was found for tunnel boring machine (TBM) [4, 43]. Cutting and normal forces effect to each other. With increase in cutting force, normal force also increases but when normal force is increases then the cutting force would decrease or unaffected depending on the clearance angle tool bit wear.

Cutting speed is defined as the measurement of bit tip speed which is generated as a result of rotating cutting drum. It is the main parameter which causes thermal stress in tool bit during rock cutting. Wear rate of steel, stellate and carbide tools is unaffected below a critical speed of 165 ft/min to 220 ft/min [25, 28]. With increasing speed beyond this critical speed, bit consumption is increases due to increase in thermal stresses [12]. Initially it was perception that increase in cutting speed has negligible effect on forces but later on it is observed that cutting force slightly increase with velocity [17]. During rock cutting, pick speeds may vary between 200 and 600 ft/min (1.0 and 3.5 m/s). Softer rocks may be subjected to higher cutting speed but in case of hard rock's high cutting speed increases the wear rate, dust generation and risk of sparking in gassy mines [51].

6. *Effect of Other Factors*

There are several other factors like thermal stress, non-rotation of tool bit during cutting, and operator's skill which also affect the tool bit wear. The thermal stress induced in tool pick during rock cutting can be controlled by medium or high pressure water jet also it helps in removing abrasive rock particle from the tool bit surface [12, 25]. Also the water pressure by which spraying is done affects normal force magnitude. It has been observed that spraying of water with high pressure, 3000 to 5000 psi, on cutting zone would reduce the normal force by an average of 30 % on a one inch cutting depth which result in reduction of bit wear [20].

The lacing of cutting tool has been done on cutting drum such that tool bit can rotate properly during cutting. This will result in uniform wear of the tool bit and sharpness of tool bit will be persisted. But it has been found that many bits did not rotate properly during cutting [28]. In this case a flat surface is formed on the tip of the conical bit due to abrasive wear which is parallel to the direction of cutting. The area of this flat surface is increased with additional rock cutting [16].

The operating skill of operator also play major role in efficient excavation of rock and wear of tool bit. Improper loading of tool bits on rock resulted in damage of tool bit surface by more abrasion or cracking than by tensile stress induced in the bit.

V. CONCLUDING REMARKS

In this study almost every aspect related to the tool bit wear has been covered. The important points have been highlighted under different headings. Following conclusions can be drawn.

1. Conical tool bits have simple design among available different type of tool bits. It can be used for a longer time with wear, as in the case of conical tool the tool bit can rotate along its longitudinal axis during rock cutting operation.

2. Abrasive nature of rock is main cause of wear of tool bits. It has been observed that wear of conical tool bit is proportional to rock strength, rock hardness and rock abrasive nature, while tool bit wear is inversely proportional to the hardness of tool bit material. On increasing speed wear rate of tool bit is increased.

3. It has been observed that the following factors related to the tool bit affects the cutting tool performance

   a. Small tip angle and longer tip length of the tool bit resulted in better cutting efficiency due to better penetration as well as less wear of tool bit.

   b. Optimum bit spacing at a depth of cut resulted in better cutting efficiency of tool bit. It has been observed that on increasing depth of cut, tool wear decreases.

4. Water spray with medium or high pressure water jet resulted in reduction of bit wear.

5. More wear on flank face than rake face has been observed.

6. Large attack angle in the range of 30˚ to 52˚ give rise to efficient rock cutting with less normal force and high cutting force. Lower attack angle resulted in more friction and heat generation during rock cutting.

7. High cutting force and low cutting speed provides better efficiency as well as better machine stability.

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