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A methodology for designing cutting drum of surface miner to achieve production of desired chip size

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Abstract. The size of coal chips, produced during coal cutting operations, is of prime importance from the viewpoint of feed size desired by power plants. Proper chip size in cutting can eliminate primary crushing and in-turn save energy. Achieving a designated size of chip is intimately linked with the drum design inter alia the wrap angle, line spacing of picks and pick size. Operating parameters namely cutting speed and drum speed also influence the output. Considering the increased need to produce a sized product for cost-effective mining, a design methodology was developed to achieve a required chip size for surface miners with a middle drum configuration. Various pick, drum and operational parameters were taken into account for the development of drum design, namely drum width, drum diameter, pick size, clearance angle, rake angle, cutting angle, lacing pattern, angle of wrap, depth of cut, indented depth of cut and pick spacing. Limiting factors for drum design such as the number of picks, pick temperature, strength of pick, depth of cut and dust generation were discussed. A new drum configuration for achieving 100 mm chip size was validated which showed close agreement with the output produced using 2200SM model surface miner.

Keywords. Chip size; depth of cut; drum; pick; surface miner.

1. Introduction

Application of surface miners (SMs) in mining projects is increasing rapidly because of their capacity for continuous and versatile selective mining, bulk production capability, reliability and cost-effectiveness. The design and fabrication of SM was ventured based on mechanical excavation principle. Design and operation of SM must aim at desired product size, higher productivity, greater pick life and reduced power consumption. The size of chip produced during cutting is very important both for producer and consumer viewpoint. Thermal power plants need sized coal with a size range between 100 and 150 mm. Such consumers even pay higher premium for this range of coal chip size to producers [1]. To achieve desired chip size it is necessary to focus on drum design parameters, namely, drum width, drum diameter, pick size, clearance angle, rake angle, cutting angle, lacing pattern, angle of wrap, depth of bite, indented depth of cut, pick spacing, pick placement at the drum ends and cutting force. The paper outlines a design methodology that can be adopted for the drum design along with selection of operating parameters forSMs with a middle drum configuration (milling type).

2. Drum design methodology

Efficient cutting is achieved if the cutting drum is suitably designed with respect to intact rock and rock mass conditions. Operating a machine without considering the rock/rockmass properties may result in overloading and loss of machine itself. The drum design must also consider the product size desired with minimum impact on the surrounding environment. Suitable criteria need to be evolved for designing a cutting drum in accordance with the target which is given below.

2.1 *Design criteria*

It is important to design a proper layout of cutting picks over the drum of SM for increased cutting performance and decreased pick wear and breakage for obtaining required

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size of cut material. The design should be made with an aim to cut maximum volume of mineral for a given power. The product should contain minimum fines and maximum of large and graded size cut material. The formation and dispersion of respirable dust also should be low. One of the most important requirements in rock cutting is to have a cutting tool capable of taking a reasonable depth of cut. Low or inadequate penetration merely produces rubbing, high pick wear and more dust. In order to secure adequate pick penetration it is necessary to maximize the pick tip cutting force and this depends on a number of basic interrelated factors such as pick speed, diameter of head, number of picks in contact and cutter motor power.

Three forms of cutting action takes place during the process of rock cutting, namely, indented depth, depth of bite and depth of cut. Indented depth of cut is the depth up to which a single pick penetrates in the rock. Depth of bite is equivalent to tool advance per revolution of drum. The depth of cut is the thickness of rock to be cut. A schematic diagram presents these cut parameters in figure 1.

In order to achieve better cutting efficiency sharp tools should be used with suitable spacing to prevent over size or under sized chip in the process of cutting. Worn or damaged tools cause higher cutting forces leading to rapid damage to tool holder, drum and gearbox, consequently reducing haulage speed apart from producing more dust and fines. It was found that all the SMs investigated during study were having conical picks. Hence, conical pick was considered for the drum design. In the drum design criteria main emphasis was on the chip size.

2.2 *Intact rock and rock mass parameters*

Rocks are heterogeneous materials and vary in their properties widely. Therefore, it is expected that there would be variation in cutting resistance offered by different rock types [2]. Intact rock and rock mass parameters are the key factors influencing performance of cutting. Literature review also highlights the increased use of compressive strength and tensile strength of rock as the most common parameters by various researchers to determine the pick cutting force. The relations developed for point attack picks by different researchers [3–5] are expressed as:

$$F_c = \frac{16\pi d^2 \sigma_t^2}{Cos^2(\varphi/2)\sigma_c} \tag{1}$$

$$F_c = \frac{16\pi \sigma_c d^2 \sigma_t^2 (\varphi/2 + \psi)}{\left[2\sigma_t + (\sigma_c Cos(\varphi/2))\left(\frac{1+Tan\psi}{Tan(\psi/2)}\right)\right]^2} \tag{2}$$

$$F_c = \frac{4\pi \sigma_t d^2 Sin^2(\varphi/2 + \psi)}{Cos(\varphi/2 + \psi)} \tag{3}$$

where, F_c = cutting force (kN), d = depth of cut (cm), σ_t = rock tensile strength (MPa), σ_c = rock compressive strength (MPa), φ = tip angle (degree) and ψ = friction coefficient between cutting tool and rock.

It is also a known fact that presence of joints, cleavage, foliations and schistocity affect the thickness of chip formed and the efficiency of cutting.

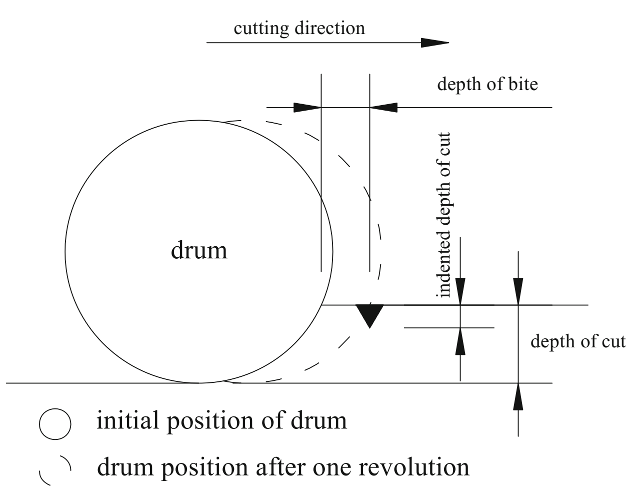

Figure 1. Cut parameters of SM drum.

2.3 *Drum parameters*

The number of picks that can be anchored on the surface of cutting drum depends on its dimension. Generally, SMs of larger engine power have large dimension of cutting drum. Production capacity of SM is governed by drum width and diameter. Both govern the sweep area of cut and thus decide the possible production under different cutting depths. The controlling factors of different drum parameters are discussed below.

(a) Drum width There are many models of SM having varied drum width. The cutting area of rock is proportional to width of the drum. The width of the drum governs the achievable angle of wrap. Width of the drum plays a paramount role in the design of lacing pattern and spacing of picks.

(b) Drum diameter The loading efficiency generally decreases as diameter of the drum is reduced. According to Peng [6] the diameter of the drum axis does not have too much to do with the cutting efficiency, but it is a major factor controlling the loading efficiency. The cutting circle diameter of 2200SM was increased from 1115 mm to 1300 mm for high working depth and high mining volumes [7]. The rate of decrease becomes more remarkable with diameter below 1.12 m. This causes recirculation of cut material as it cannot be moved quickly enough across and out of the drum. The diameter of drum helps in designing number of picks for each angle of wrap. The depth of cut and in turn number of picks coming in contact with rock depends on diameter of drum.

2.4 *Pick parameters*

Various types of picks are used for rock cutting such as radial and conical (also called point attack) as shown in figure 2. These picks require relatively low forces to cut rock and are also economically viable. The study made by Plis *et al* [8] indicated that conical picks with tungsten carbide inserts could provide a substantially longer and more efficient life than radial picks with similar inserts. According to Hurt and Evans [9], Hurt and McAndrews [10] conical picks were considered to be more practical than the wedge type picks. Conical picks have their shanks inclined at 35°–55° towards the cutting direction. Conical picks have cylindrical shank; shank axis being inclined towards cutting head radius. Cutting action induces pick to rotate, resulting in a sharpening effect. The pick rotating freely in the holder distributes wear evenly, significantly increasing the pick life and reducing machine down time for pick changes [11]. Hence, SMs predominantly use conical picks for rock cutting. A typical attachment of conical picks to the cutting drum is shown in figure 3. The conical pick initiates breakage of rock ahead of the tool. Major fractures induced in this way result in the removal of saucer shaped pieces as the rock breaks at a shallow angle on both the sides and ahead of tool.

The tool clears the path and forms groove on rock as shown in figure 4. Description of various pick parameters is discussed below.

(a) ***Size of pick*** Tool diameters are of two types, namely, small diameter and large diameter as shown in figure 5. The small diameter tungsten carbide cutting tools have low life, good penetration, high cutting performance and coarse gradation whereas large diameter tungsten carbide tools have long life, poor penetration, low cutting performance and fine gradation.

Figure 3. Point attack picks used in SM.

Figure 4. Profile of grooves with spacing of cutting tools.

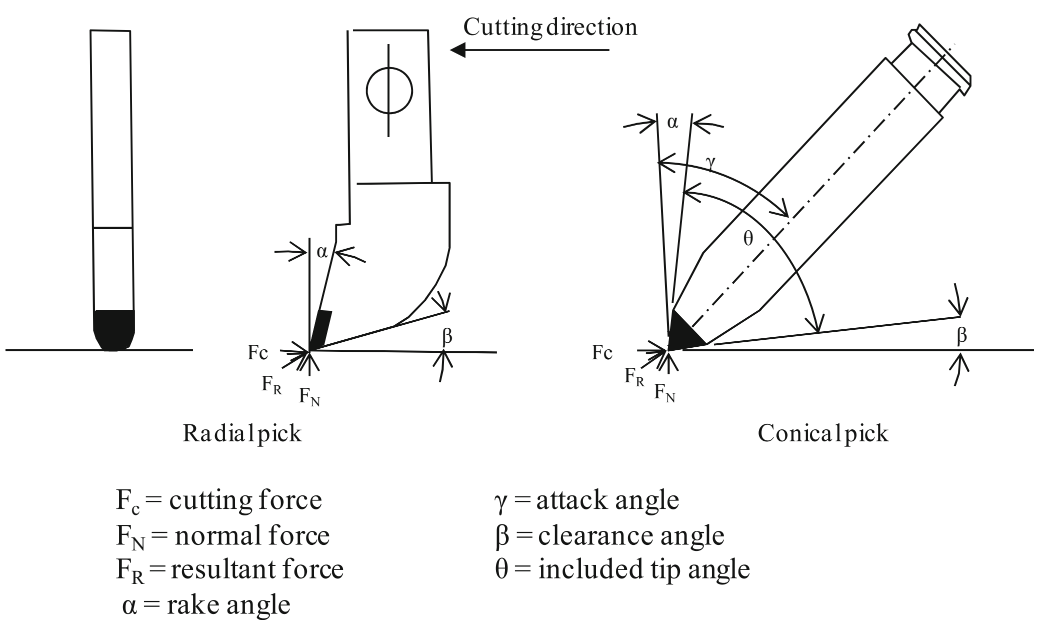

Figure 2. Design of radial and conical pick.

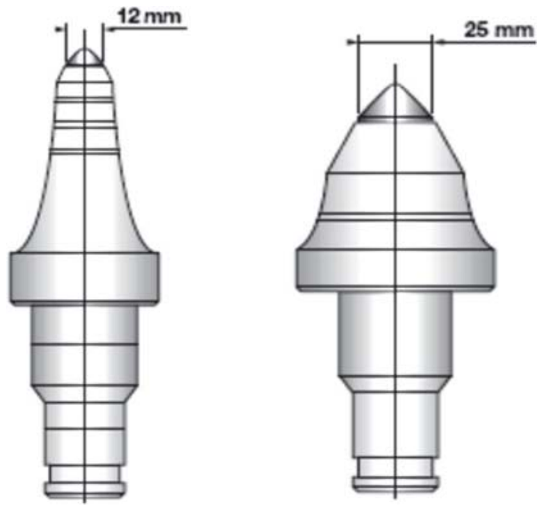

Figure 5. Small and large diameter tungsten carbide conical pick.

Large diameter picks are more efficient than small ones. They can commensurate with the cutting force and more particularly with the cutting force fluctuations that SM can withstand. Larger diameter carbide pick tip can cut stronger rock. Larger tip angle (70°–80°) is preferred for stronger rock. An increase in the cone angle of the carbide tip leads to linear increase in the cutting and feed forces [12]. The radius of the curvature of the carbide tip has a non-linear effect on the state of loading of the conical bits. The projection of the carbide insert and the diameter of the shoulder of the shank should be so selected that the shank does not go beyond the surface of the carbide insert. The angle of taper of the shank should be taken up to 30°. 12 mm diameter conical pick was considered in this study. The dimension of the pick is shown in figure 6.

(b) ***Clearance and rake angle*** The strength of the tool tip is determined by clearance angle and rake angle. As clearance angle is increased a tool tip becomes weaker

Figure 6. Dimension of the pick used in drum design.

because it loses the support of the tool body. Bits with a smaller clearance angle wear-out more rapidly which leads to increase in cutting loads. Generally back clearance angle should be greater than 5° and less than 10° for efficient cutting with point attack tool. During cutting, the cutting edges wear down and the clearance angle reduces. Care should be taken that tools are anchored with positive rake angle of approximately 10°. The front rake angle should be made as large as possible but generally not greater than 20°. If large tip angle is necessary, it is preferable to maintain the clearance angle with reduced rake angle. Transition of breakage mode (from tensile to shear) when rake angle increases beyond 18 degrees is also worth considering while designing the pick configurations on drum [13].

(c) ***Cutting angle*** The minimum energy consumption in coal cutting is achieved for cutting angles in the range of 55°–65°. But in most of the cases picks are fitted with cutting angles between 65°–85° and sometimes more. This is mainly because bits are designed to give greater strength required for cutting. Angle of skew up to 30° has no effect on the measured cutting force. The cutting angle (γ) should not exceed 85° as shown in equation (4) [7].

$$\gamma = \beta + \theta \leq 85^{\circ} \tag{4}$$

where γ = cutting angle, β = clearance angle and θ = bit angle.

(d) ***Lacing pattern*** The recommended minimum lacing for normal cutting condition is 1.5 times the width of the tool tip. Minimum distance between point attack holders for heavy duty machine should be 225 mm [14].

(e) ***Angle of wrap*** According to Murthy [13], the minimum angle of wrap should be 210° for a 2-start drum, 140° for a 3-start drum and 105° for a 4-start drum, i.e., the total of the minimum angle of wrap should be 420° for shearer drums for effective loading of cut material. The cut material is pushed towards the centre of the drum of SM and hence drum spirals are in the form of twin helix. This type of picks arrangement is termed as chevron pattern. Therefore, half width of the drum should be considered for designing the angle of wrap.

(f) ***Depth of bite*** Deep bites with wide lacing results in efficient cutting. Deeper bites promote a wider breakout, so that pitch lines can be widened, reducing the number of picks employed around the drum. Pick spacing can be increased by reducing their number for a given width of drum and keeping same lacing pattern. Deeper bites result in minimum tool requirement and remove a major portion of space shortage for placement of large number of tools. Deeper bites will lead to larger chip size. The size of chip is the distance between the successive trajectories of cutter bit passing perpendicular to the cutting surface. The cutting force is directly proportional to the thickness of chip. Deeper bites per revolution can be reduced by modern technique known as counter laced cutting pattern so as to achieve smaller chip size of mineral.

(g) ***Indented depth of cut*** The depth of pick penetration in the mass is influenced by brittleness of rock, geological condition, thickness of chip, type of cutting, shape of cutting edge to surface of cutting edge, cutting angle, bit angle and bit attachment. The maximum cutting depth is limited either by the reaction force of the rock or by the maximum depth of bite and by the design of the cutting head. The effect of shallow and deep indented depth of cut is shown in figure 7. The mean value of the indented depth (di) of cut is a function of the thickness (h) of chip and is expressed by Pozin *et al* [12] as:

$$di \approx 0.45\sqrt{h} \tag{5}$$

where, di = indented depth of cut (cm) and h = thickness of chip (cm).

(h) ***Pick spacing*** Pick spacing depends on indented depth of cut. The effect of spacing between cuts and indented depth of cut (penetration) on cutting efficiency is explained in figure 8. If the line spacing is too close (a), the cutting is not efficient because the rock is over-crushed. Tool wear is also high due to the high friction between tool and rock. This was well demonstrated in Johson and Fowell's work [15].

This was explained as insufficient penetration resulting in rubbing and inefficient unrelieved cutting, which in turn increased tool consumption significantly. If the line spacing is too wide (c), the cutting is not efficient since the cuts cannot generate relieved cuts (tensile fractures from adjacent cuts cannot reach to form a chip), creating a groove deepening situation which creates shock loads causing gross failures in cutting edge. Hence, optimum spacing (b) is vital for proper chip formation.

The optimum ratio of cutter spacing to depth of cut generally varies between 1 and 5 for pick cutters. In general, the spacing between picks should be between two and three times the indented depth of cut for maximum cutting efficiency. According to Evans [3], spacing for the point attack pick is expressed as:

$$Ps = 2di\sqrt{3} \tag{6}$$

where, Ps = pick spacing (mm) and di = indented depth of cut (mm).

(i) ***Picks at drum ends*** Picks placed at the periphery of the drum create face and consequently more cutting force is required by these picks. Therefore, the density of picks is kept high at drum ends to reduce the applied load per individual pick. Measurement of pick layout at the edge was done in the study carried out for the drums of 2200SM and 2500SM. It was found that at the ends of the drum, picks were placed at 1/3rd of linear pick spacing with skewed angles as shown in figures 9 and 10, respectively. Hence, all these conditions were taken into consideration for the drum edge design. For edge protection of drum, a

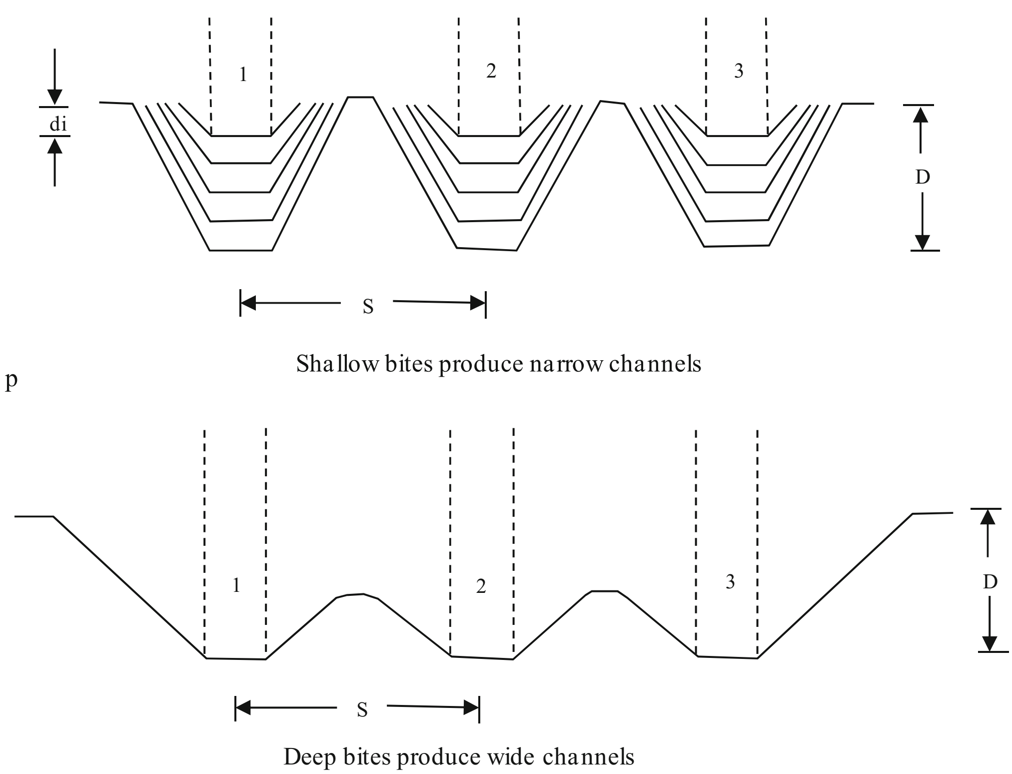

Figure 7. Shallow and deep depth of bites.

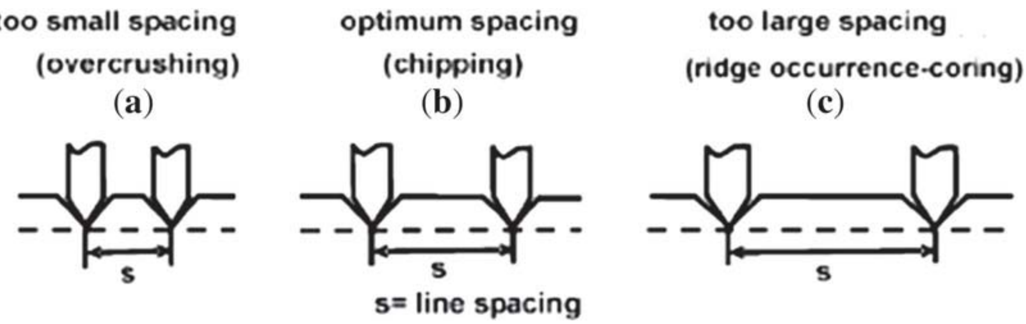

Figure 8. Pick spacing with indented depth of cut.

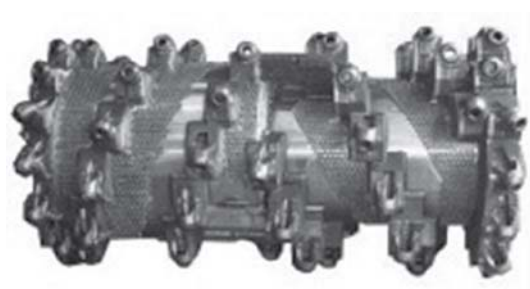

Figure 9. Pick box arrangement of 2200SM SM [16].

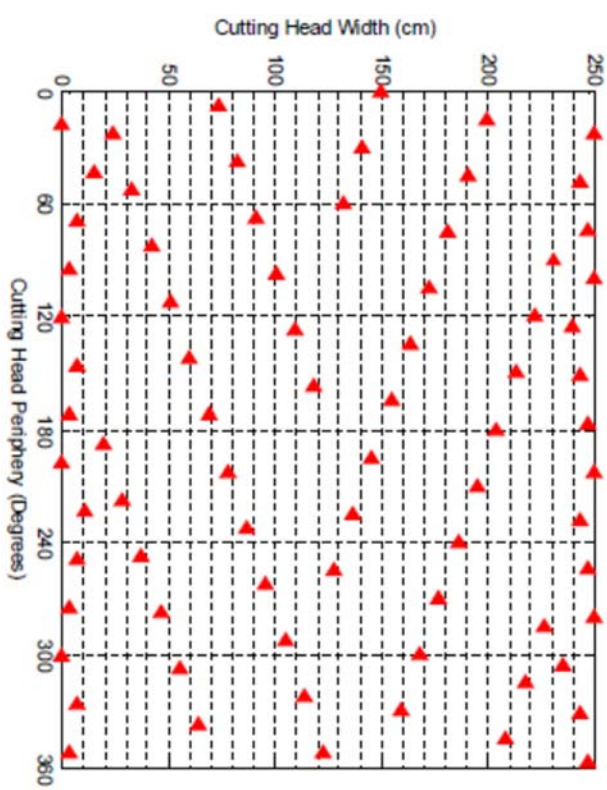

Figure 10. Picks arrangement of 2500SM SM.

few picks are found to be projected outside the width of the drum.

3. Limiting factors for drum design

(a) ***Number of picks*** The number of picks depends on drum width and drum diameter. The placement of picks is governed by the size of pick holders. Hence, there is restriction in number of picks that can be placed on a drum. For a strong rock it may not be possible to lay the required number of picks for small dimension of drum.

(b) ***Pick condition*** The pick condition should be carefully inspected. The cutting capacity of the pick greatly reduces as the worn area increases and this leads to increase in cutting resistance. The worn out picks pose problem of frictional ignition in coal and reduces the cutting capacity. The potential risk of sparking while cutting depends on the drum speed, silica content, bands, rock type and sharpness of tool.

(c) ***Pick temperature*** If the SM is operated continuously for prolonged hours, temperature of the cutting picks increases. Picks at higher temperature wear at a faster rate. Hence, there should be proper water jet arrangement for cooling of picks and the nozzles should not get blocked by the cut materials during the process of cutting. Drum speed and cutting speed may become a limiting factor for controlling the hazard of incendivity for sparking [17].

(d) ***Pick strength*** Maximum allowable cutting force by the pick depends on strength of the pick. The pick material should be of good quality so that it can withstand maximum possible cutting force. Technological developments should be consistent with the requirements of performance, reliability and durability. Selection of a suitable composition of tool with high wear resistance would be useful for rock conditions with high abrasivity. Pick breaking load was considered to be 120 kN in the study.

(e) ***Rock properties*** The size of chip or the depth of bite by the cutting drum is governed by strength of rock. Large chip size can be obtained for low strength of rock and vice versa. Higher speed of cutting on greater strength of rock will overload the pick and the cutting motor of the SM. This may consequently lead to more dust generation also. It is necessary to determine suitable cutting force at varied indented depth of cut which the pick can withstand. Pick breaking load needs to be determined considering the intact rock and rock mass strength. Dynamic impacts also need to be considered here.

(f) ***Depth of cut*** The depth of cut is governed by the intact rock and rock mass parameters and available machine cutting power. Maximum depth of cut also has its limitation with drum diameter as specified by manufacturers of SM.

(g) ***Dust generation*** If the amount of cut material exceeds the free volume of the drum, then excessive clogging occurs at the drum and hence dust generation is aggravated. Therefore, the angle of wrap should be kept minimum so that the travel length of the cut material is least.

4. Drum design for a given chip size

The requirement of size of chip for power grade coal in the power plants generally ranges around 100 to 150 mm as discussed earlier. Drum design is framed for 100 mm chip size requirement under ideal rock condition, i.e., pick can easily cut the rock and the rock is free from joints. Hence, this chip size can be considered as theoretical. All the conditions mentioned in sections 3 are taken into consideration for the drum design.

4.1 *100 mm chip size*

The approximate indented depth of cut, as per equation (2), comes to 14 mm for obtaining 100 mm chip size of cut material. The ratio of pick spacing and indented depth of cut should be maintained in such a way that specific energy consumption in cutting is minimum, which can be analyzed through laboratory investigation. It is advisable to approach this procedure for site-specific drum design and better performance of machine. The pick spacing, as calculated from equation (7), comes to 49 mm. Thus, the number of picks required for a drum width of 2200 mm is 46 which can be calculated as:

$$Pn = \frac{DW}{S} + 1 \tag{7}$$

where, Pn = number of picks, DW = drum width (mm) and S = pick spacing (mm).

This relation excludes the picks at drum ends. The lacing pattern and the pick placement depend on the drum diameter. The layout of pick placement for a typical 1140 mm drum diameter is represented in figure 11. The minimum distance between the pick holders was kept at 225 mm. The number of starts comes to 1.43. The number of starts has to be in a round figure. Hence, in order to have one start the minimum angle of wrap comes to about 516° for the half width of the drum for smooth and rapid flow of cut material towards the centre of the drum.

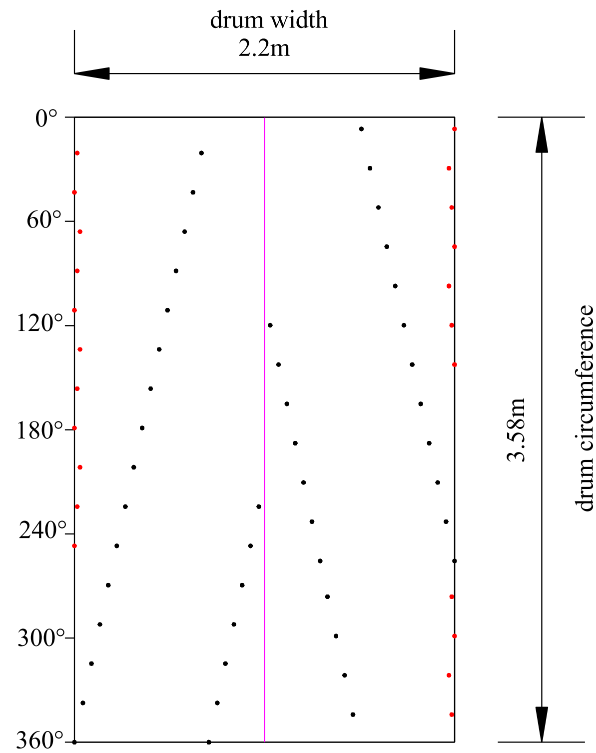

Figure 11. Layout of pick arrangement for acquiring 100 mm chip size [18].

The angle of wrap can be increased by extending the position of picks on the lace (vane) maintaining the same line spacing of picks. A general drum design for 2200 mm width of machine for different chip sizes is given in Table 1. Pick spacing and total number of picks, mentioned in the table, is the minimum requirement to achieve the desired chip size. If the pick spacing is reduced and the number of picks are increased for the same rock type the chip size reduces as shown in figure 12 [7]. The optimum chip size can be obtained for a given rock type by laboratory test. However, manufacturers fix higher number of picks to the circumference of the drum so that SMs can be operated smoothly in varied rock conditions. The drum design is not inclusive of influence of rock mass properties as discussed in section 2.2.

5. Validation

The average chip size was validated for drum specification of 2200SM SM deployed in Sonepur Bazari opencast mine of Eastern Coalfields Limited (ECL) located in the eastern part of Raniganj Coalfield, West Bengal, India (table 2).

Table 1. General drum design pattern for different chip sizes.

	Chip size (mm)			
Specifications	50	100	150	200
Drum width (mm)	2200	2200	2200	2200
Pick spacing (mm)	35.0	49.0	60.0	70.0
No. of picks	64	46	37	33
No. of picks for half drum	32	23	19	17
Drum diameter (mm)	1140	1140	1140	1140
No. of starts (Theoretical)	2.01	1.43	1.18	1.02
No. of starts (Actual)	2	1	1	1
Angle of wrap (degree)/start	362	516	423	368
No. of picks at drum edge	22	22	22	22
Total no. of picks	86	68	59	55

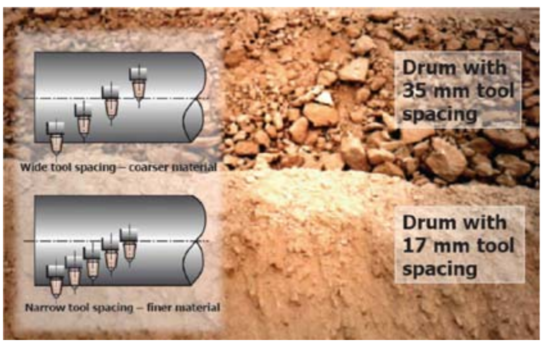

Figure 12. Chip size variation for same rock type by altering pick spacing.

Table 2. Technical specifications of 2200SM model SM.

Parameters	2200SM
Cutting width (m)	2.20
Cutting depth (m)	0.35
Drum diameter (m)	1.14
Travel speed (km/min)	0-5
Engine (HP)	800
Weight (t)	51.0
No. of tools	76
Pick spacing (mm)	38

Fragalyst-4.0 software, developed jointly by Central Institute of Mining & Fuel Research (CIMFR) and Wavelet Group, was used for the chip size analysis as shown in figures 13(a) and figure 13(b). The average cut size (K_{50}), obtained using Rosin-Rammler equation, after correction for the fines in three different locations is given in table 3. The overall chip size of the coal obtained by the analysis was 130 mm.

For 100 mm chip size the minimum number of picks should be 68 as per new design though the actual number of picks of 2200SM SM was 76. There was not much

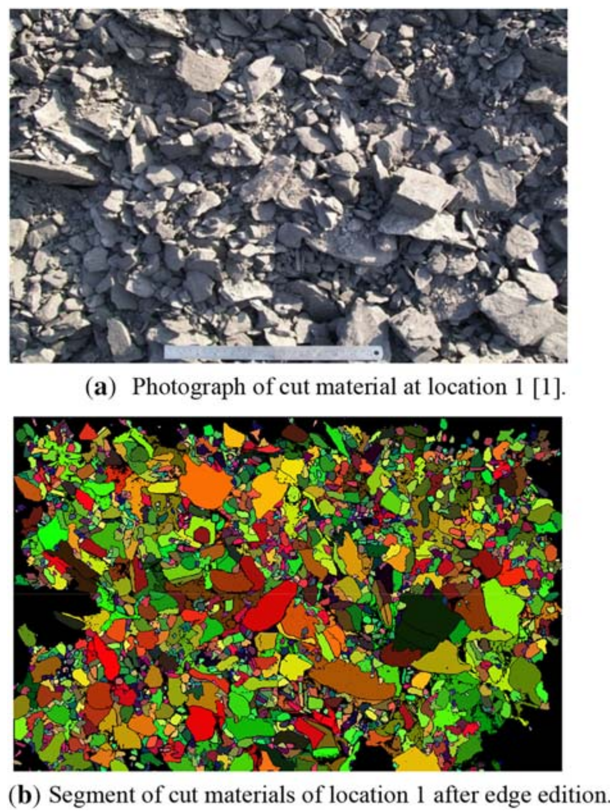

Figure 13. **(a)** Photograph of cut material at location 1 [1]. **(b)** Segment of cut materials of location 1 after edge edition.

Table 3. Mean chip size obtained at Sonepur Bazari opencast mine, ECL, India.

Location no.	K_{50} (mm)	Joint spacing (Js) (cm)
1	60	Js > 50
2	200	Js < 20
3	130	20 < Js < 50
Average	130	

deviation in the average chip size despite not considering the rock mass condition.

6. Conclusion

A design methodology was developed for SMs with middle drum for obtaining a given chip size. The same was validated for the chip sizes ranging from 50 to 200 mm. The drum design parameters, namely, line spacing, angle of wrap and number of picks, determined using the suggested methodology, are in close agreement with the parameters of one of the existing SMs. The new drum configuration for achieving 100 mm chip size was validated with the chip size generated by 2200SM SM and the result was found to be close to the actual. Incorporation of rock mass condition in drum design would further refine the end result which requires more investigations.

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