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Suggested methods for optimum rotative motion of point attack type drag tools in terms of skew angles

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ABSTRACT

Rotation of point attack picks in their tool holders is of crucial importance for an efficient performance of machines used for tunnelling and underground excavations of rocks and coal. With current machines, skew angle has been extensively employed to achieve tool rotation. There has, however, been no common definition and suggestion on application of skew angles, due to the differences between the results of research investigations conducted in this field. This paper sets out the findings of long-term practical research during tunnelling and underground excavation operations with roadheaders and drum shearers in order to bring a common understanding in rotation of point attack picks. Mechanism of tool rotation was discussed, and a number of formulas were derived and suggested for optimum cutting conditions for roadheaders and mechanical miners, respectively. The results showed that with drum shearers tool rotation is possible without skew angles, due to the asymmetry between adjacent grooves which generates sideways forces inducing rotative movement of picks. Skew angles were, however, found to be a must for roadheaders in consideration with tool holder damage which was significantly influenced by different settings of skew angles. Furthermore, point attack picks with small-diameter shanks were found to suffer from shank breakage resulting from high values of tool forces, when fitted on the nose portion of roadheaders cutting heads.

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1. Introduction

Point attack type drag tools have been extensively used for mechanical excavation of soft and medium strength materials in tunnelling and various underground excavation operations. These picks have conical tip with tool axis diagonally positioned to the direction of cutting, thereby being called pencil point or tangential picks. Their ability in tackling relatively hard and abrasive cutting conditions is claimed to stem from ‘self-sharpening’ feature resulting from free rotational motion of tool shank in the holder during cutting. The point attack picks are, however, subject to rapid destruction if they lack this rotational ability. Under such circumstances, heavy damage will be inflicted on tool holders, and consequently the whole cutting operation is disrupted. It is, therefore, of crucial importance to sustain the rotary motion of point attack picks in their tool holder as long as the tools are engaged in cutting. Steel quality, proper clearance between the tool shank and tool holder, and prevention of dirt ingress are obviously the first step considerations for tool rotation. Introduction of a skew or offset angle with respect to the line of cutting, as depicted in Figure 1, is claimed to induce tool rotation during cutting.

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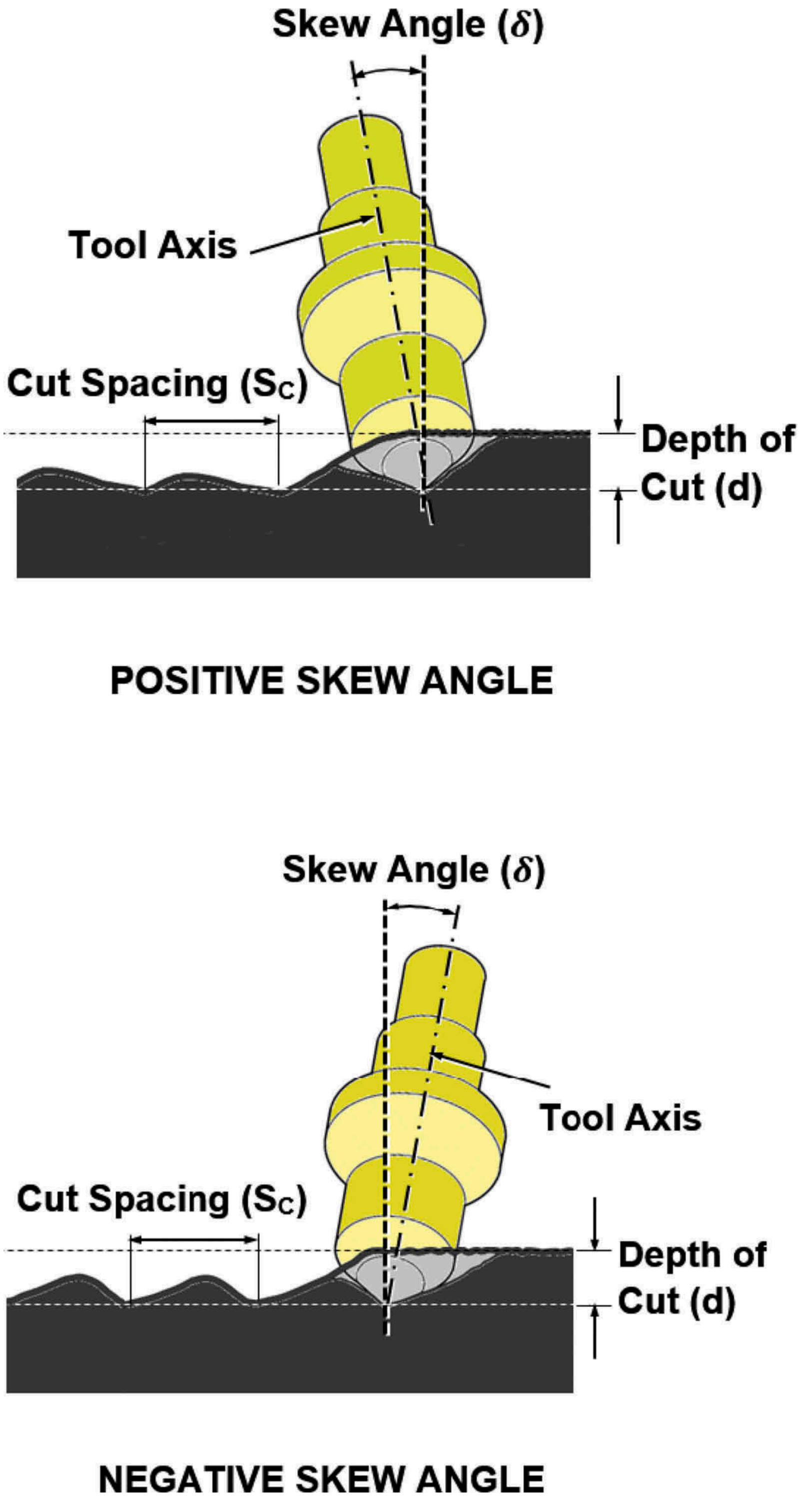


Figure 1. Definition of skew angle in laboratory linear cutting conditions.

There have been considerable studies conducted on skew angle, and nearly all of these investigations were carried out in laboratory conditions. Hurt and Jones carried out a number of linear cutting trials on the effects of skew angle ranging from zero up to 30° [1]. It was reported that up to 30°, skew angle had no great effect on the measured cutting forces, although there was some indication of a minimum mean cutting force at about 15° skew angle. They also noted that in some cutting conditions, the tool did rotate in its holder, but this idea did not result in self-sharpening, as the tool tip wears in a symmetrical pattern to approximately twice the angle of attack imposed on it. Tecen carried out laboratory linear cutting trials with point attack picks with 0°, 6.5° and 13° skew angles, respectively, at 45° angle of attack on a sandstone [2]. He revealed that tool forces with 6.5° skew angle were lower than those of 0° and 13° skew angles, while noting no visible tool rotation during these trials. It was suggested that with axial type roadheaders cutting heads, the offset angle can be a minimum of 8° and as high as 35° at the nose section, while recommending the value of 8° for transverse heads to some extent [3]. Hurt and MacAndrew suggested that the tool rotation can be achieved, provided that: (1) both the pick and the holder are of the correct dimensions and quality; (2) the angle of attack is 50–52°; and (3) the tool holders are regularly cleaned out [4]. Myren et al conducted laboratory trials on tool rotation at skew angles ranging from −10° to +10°, and reported that a 10° negative skew angle and 35° attack angle produce the maximum rotation. They further stated that a negative skew angle produced more rotation than a positive skew angle [5]. Frenyo and Lange reported that tool rotation is possible if the pick forces are able to create a torque and do not act through the tool axis [6]. They also claimed that rotation occurs not during cutting but when making contact with and when running out of the rock material. They recommended skew angle of 10° for slender tools when operating at large penetration depth, and 25° for large diameter tools at shallow depths. Kim et al investigated impact of skew angle, depth of cut and spacing on bit rotation through full-scale laboratory linear cutting tests on sandstone [7]. They reported that no systematic bit rotation occurs when bit is fully engaged and is under load, and there was no relation between bit rotation and skew angle, as well as depth of cut. Correlation between the skew angle and the temperature increment at tool tip was examined by using a granite wheel on a bench-scale device [8]. It was stated that the precursor of friction ignition (i.e., bit tip temperature) increases with the skew angle of a cutting tool. Kim et al carried out similar tests on a granite wheel to study the influence of skew angle on bit temperature, bit wear, and rock cutting performance [9]. These results inferred that the effects of skew angle on bit temperature, bit wear, and rock excavation performance are greater when bit tip surface area is large. Park et al conducted a research study on cutting efficiency and structural stability of point attack picks at skew angles ranging from −10° to+10°, by using mortar specimens of various strength through laboratory linear cutting experiments [10]. They stated that a positive skew angle appears advantageous in terms of both cutting efficiency and structural stability.

The laboratory experiments inevitably yield valuable results, since they provide full control on monitoring the variations in specific parameters without any intervention of other unexpected factors. At the other end, in situ investigations are, perhaps, more rewarding and realistic, as they clearly picture the complete outcome of the research. Such field investigations are, however, expensive and difficult to conduct, since they require near-uniform excavation conditions for a rational comparison of parameters. This may probably explain why there are no comprehensive in situ investigations in the published literature in this field. A comparison between point attack picks and radial tools was made through long-term underground investigations with coal shearers and roadheaders [11]. It was revealed that with the drum shearers the point attack tools performed successfully without any skew angle, while with roadheaders the effects of skew angle on tool rotation required special attention on protection of tool holders. No comprehensive details accounting for mechanism of tool rotation with respect to skew angle were, however, given in this investigation, since the main subject was concerned with comparison of radial and point attack type picks, rather than tool rotation. The practical findings of this research study will, therefore, be evaluated in details, here in this paper.

It is understood that there have been, hitherto, no sound definition and suggestion on application of skew angle, due to differences between the findings of the above-mentioned laboratory research studies. Moreover, there are also significant differences between the findings of the in situ investigation and laboratory studies, e.g. the skew angles suggested by laboratory trials resulted in failures during practical investigations. Furthermore, it has also been observed in practice that skew angles were set in different manners by machinery manufacturers. This is probably due to a lack of conclusive information in this field.

This paper aims at bringing a common understanding in application of skew angles for roadheaders and drum type mechanical miners, in considerations with the findings of the underground and laboratory investigations available in this field. Further long-term underground trials were also carried out with heavy-duty point attack picks on drum shearers. A dynamic and kinematic analysis on the mechanism of tool rotation related to the machines like drum shearers, continuous miners and roadheaders was made. The results were presented and discussed in details. A number of formulas were derived and then suggested for optimum rotational motion of point attack picks with respect to skew angles.

2. Methods and experimental setup

This research investigation is based upon a number of long-term underground trials carried out with drum shearers and roadheaders, respectively, during actual production operations and gateroads drivages at two different coal mines in Turkey. The first underground trials were carried out at Middle Anatolian (OAL) Lignite Mine of Turkish Coal Enterprises (TKI) which has now been privatised. The second part of the underground trials took place at Eynez Underground Coal Mines within Province of Manisa.

With drum shearers, the skew angles were investigated for two different tool lacing patterns with the picks of slender type and heavy-duty types, respectively. Practical investigations with roadheaders also involved the use of two different pick types with light-duty and medium-duty roadheaders. Utmost care was paid to conduct the all underground trials under near-uniform face and machine conditions in an effort to achieve a realistic comparison of skew angles at different setting values.

2.1. Underground trials at OAL Lignite Mine

Description of the trials together with information about this mine is not going to be mentioned here, since they were described previously [11]. The underground trials in OAL Mine involved drum shearers and roadheaders, respectively.

2.1.1. Trials with drum shearers

In this mine Eickhoff EDW-230 type double drum shearers were used to cut two coal seams with 1.5 m and 2.0 m thickness, respectively. The drums were fitted with Kennametal U40 HD slender type point attack picks having 45° angle of attack (Figure 2(a)). The specifications of the drums relevant to the scope of this study are given in Table 1, as Drum 1.

The trials were initially conducted with the manufacturer's drums having triple-tracking (three tools per line) lacing arrangement where no skew angle was introduced for both vane and clearance ring picks, i.e. skew angle was kept zero for all drum and operating conditions. The second trials involved drums with single-tracking lacing. For this purpose, the manufacturer's original drums were re-laced by the author of this paper, and then put into trials, under the same conditions. The wear characteristics of these slender-type point attack picks were continuously monitored during the production operations in longwall panels. No tool damage due to nonrotating was seen throughout the process of these long-term investigations. All the vane picks and clearance ring picks fitted on both the original drums and the redesigned drums performed uniform wear. The trials indicated that the slender type point attack picks rotated successfully without skew angle.

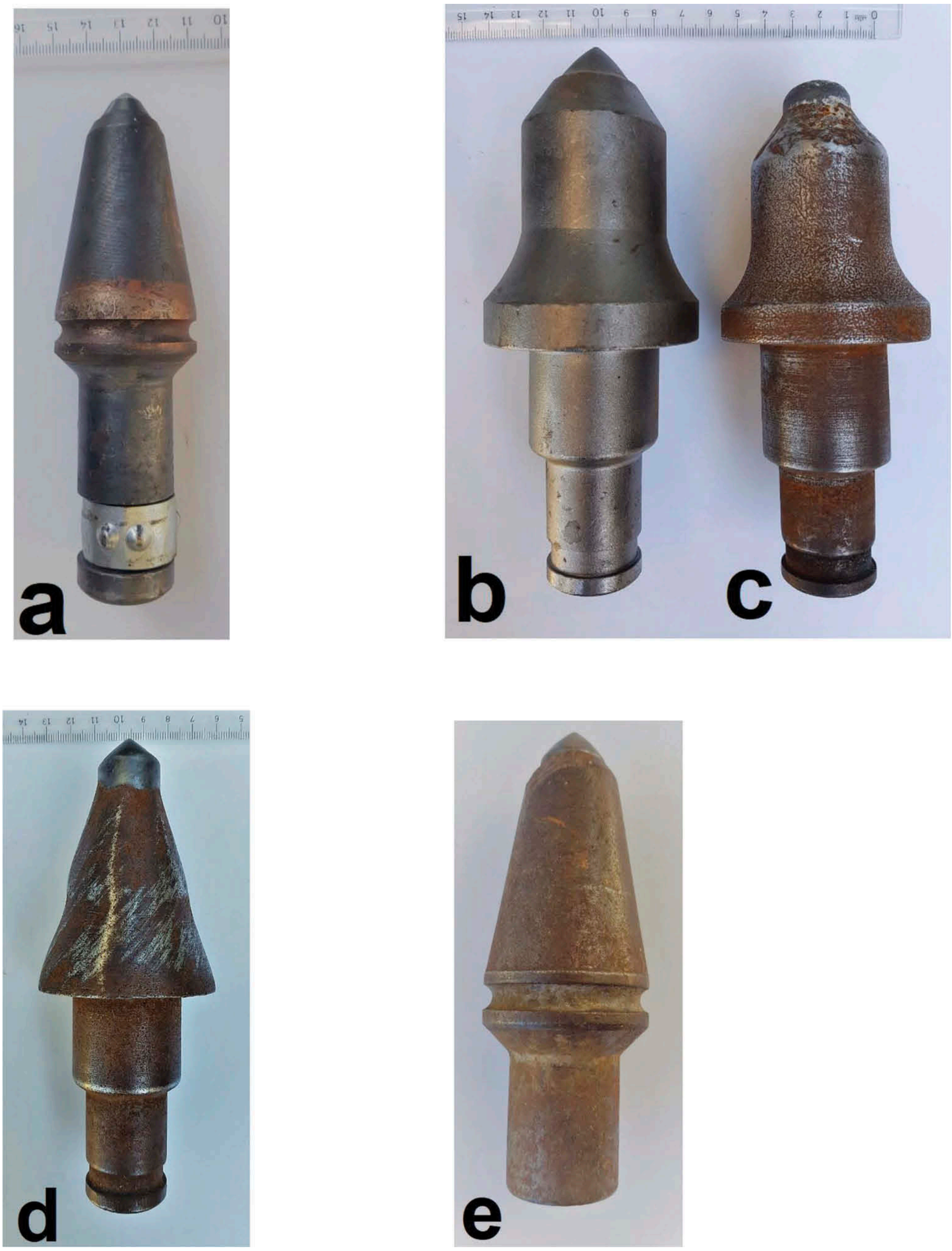


Figure 2. Types of point attack picks employed for underground investigations, (a) slender pick, (b) a pristine large-diameter pick, (c) a uniformly-worn large-diameter pick, (d) a prematurely-worn large-diameter pick, (e) a slender pick with broken shank.

2.1.2. Trials with roadheaders

The investigations were carried out during gateroads drivages with Dosco Mk2A (light duty) and Dosco Mk2B (medium duty) roadheaders fitted with slender-type and heavy-duty type point attack picks, respectively. A number of cutting heads were designed with skew angles at three different settings, and then put into long-term underground trials during gateroads drivages. Description of each setting together with the results obtained is given below:

Table 1. Specifications of drums and operating conditions.

		Drum I	Drum II
Total installed power (Kw)		230	300
Drum Diameter (m)		1.60	1.40
Drum Width (m)		0.80	0.60
Number of Spirals		3	3
Angle of Wrap (degree)		270	120
Drum Speed (RPM)		36	43
Maximum Advance per Revolution (cm)		9.5	9.0
Cut Spacing (cm)	1 tool per line (Single-tracking)	9	9
	3 tools per line (Multi-tracking)	6	8
θ	1 tool per line (Single-tracking)	30	23
	3 tools per line (Multi-tracking)	20	20
β	1 tool per line (Single-tracking)	4.76	3.46
	3 tools per line (Multi-tracking)	4.76	3.58
β_S	1 tool per line (Single-tracking)	11.31	10.62
	3 tools per line (Multi-tracking)	14.04	10.72
$\beta \neq \beta_S$ condition		satisfied	satisfied

Setting I: The tool axis was tangentially positioned to the radial line at the tip of the pick, as illustrated in Figure 3(a). With this arrangement, tool rotation was achieved at the expense of notable damages occurring on the left-hand side of tool holders related to the picks close to the cutting head nose.

Setting II: The axes of all tools were skewed by a fixed value of 8° with respect to the line which is tangent to the radial line at the intersection with the tool tip, as shown in Figure 3(b). With this arrangement, all tools exhibited rotation which was evident from uniform wear. It is important to note that damage at left side of tool holders was developed more rapidly than that observed with setting I described above. This situation consequently resulted in cutting head replacement.

Setting III: The radial line perpendicularly passed through the tool axis in such that both of them intersected at a point on tool plan length (Figure 3(c)). By virtue of this arrangement, a skew angle was inherent in each tool, and its value depends upon cutting radius and corresponding plan length of the tool axis. The skew angles were in opposite direction to that adopted in setting II. During these practical trials, the roadheaders were laced with large-diameter point attack picks being Kennametal U47 heavy-duty type and Kennametal U 40 HD slender type picks, respectively. The radial line was shifted away from the tool tip with a distance being equal to the plan length of pick gauge along the tool axis. It is to note that the radial line was always perpendicular to the tool axis, as depicted in Figure 3(c). The resultant skew angles for each tool were, then, calculated, as follows:

$$\delta = tan^{-1}\left[\frac{l\cos\varphi}{r}\right] \tag{1}$$

where $\delta =$ Skew angle (degree), l = Pick gauge or tool reach, measured along the tool axis (mm), r = Radius of the given pick (mm) and φ = Angle of attack (degree).

It is to note that the value of skew angle varied from 0° up to 30° while moving towards the nose portion of the cutting head with this setting. Large-diameter point attack picks were seen to rotate successfully without any failure, and no significant tool holder damages were seen throughout the cutting operation, despite the presence of hard siliceous inclusions on the face. It is very important to emphasise that large-diameter point attack picks exhibited the best performance with this setting among all setting values, Shank breakage was, however, seen to occur with the slender-type picks located close to the nose portion, in spite of successful rotation (Figure 2(e)).

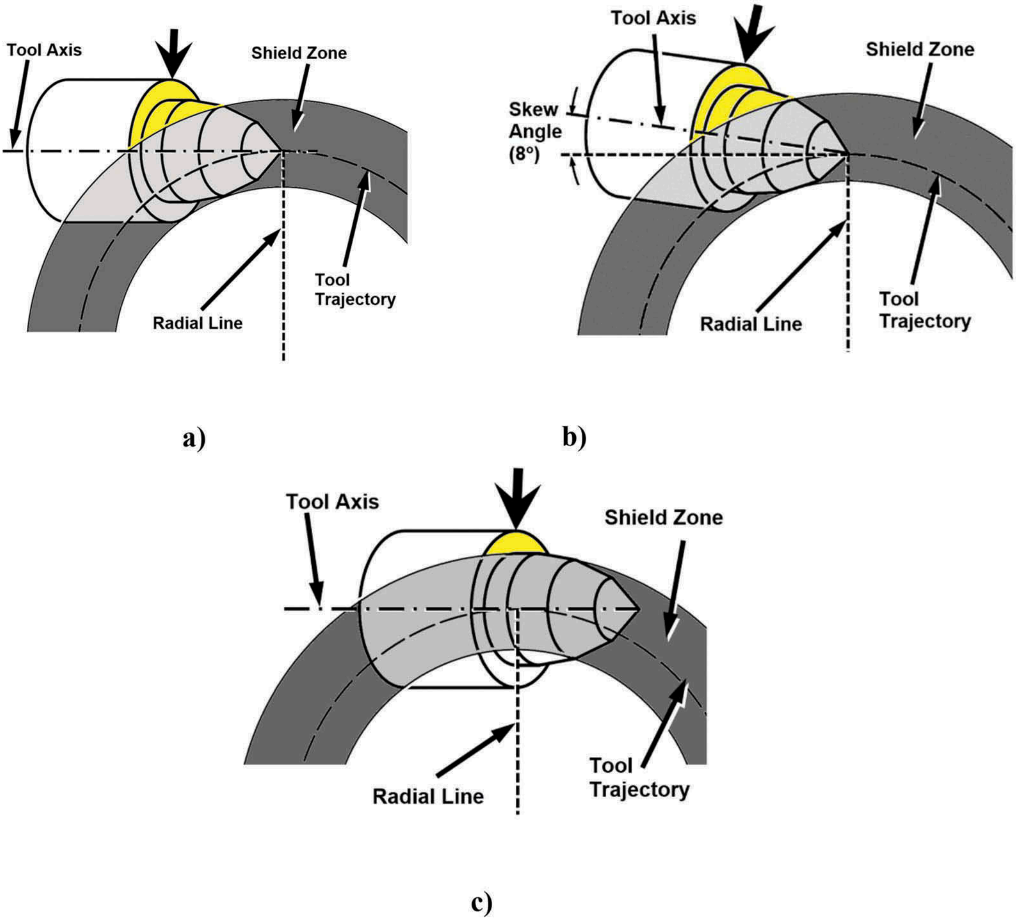


Figure 3. Setting skew angles with respect to the radial line; (a) radial line at the tool tip, (b) a fixed skew angle of 8° with radial line at the tool tip, (c) radial line behind the tool tip.

2.2. Underground trials at Eynez Lignite mine

This underground mine is located at Soma Coalfield in Aegean Region of Western Turkey, which is run by Imbat Mining Company. In this mine, coal seams of 20 m thick were extracted by longwall top coal caving methods with a production rate of 6 million tons per year. Underground trials carried out in this mine involved drum shearers only. Famur drum shearers having 1.40 m drum diameter and 0.60 m web depth were employed. Each drum was fitted with a total of 33 large-diameter point attack picks having 48° angle of attack, being equivalent to Kennametal U47 1SM types (Figure 2(b)). The original drums were arranged in three starts with three tools per line (triple tracking or multi tracking). The specifications of these drums relevant to the scope of this study are given in Table 1, as Drum 2.

Long-term observations were initially conducted with these original drums to investigate rotative motion of large-diameter point attack picks. Along with the manufacturer's triple tracking design, the same drums were also redesigned by the author to obtain one tool per line (single tracking) arrangement in an effort to compare two different lacings in terms of tool rotation. It should be noted that with both designs no skew angle was introduced for both the vane and clearance ring picks. No drawbacks arising from nonrotating was seen for all drums throughout the process of these long-term investigations. All the vane picks and clearance ring picks fitted on both the original drums and the redesigned drums exhibited uniform wear as presented in Figure 2(c). It is important to note that a type of uniform wear as shown in Figure 2(d) was also seen, though being very rare, with drum shearers. This is a kind of premature wear occurring occasionally, similar to that known as 'steel wash' mainly due to re-circulations of cut materials around the drum. It was not, hence, counted in a uniform wear.

The results of these underground trials showed that the large-diameter point attack picks rotate successfully in their tool holders without introducing any skew angle, regardless of the difference between the lacing pattern. This is also in good agreement with the finding of the trials with slender type point attack picks for two drums of different lacing.

3. Discussion

3.1. On tool rotation with drum shearers

The laboratory studies generally suggest skew angles around 8° to 15° for rotation of point attack picks, whereas the in situ trials showed different trends. The most interesting of all is that the condition of tool rotation with drum shearers exhibited a different trend from that of roadheaders in terms of the value of skew angle.

It would be useful to consider the position of tool axes with respect to pick trajectories described by tools fitted on drum shearers in order to bring a better insight into this discussion. With drum shearers, the vane picks are usually arranged in the form of parallel-axis tools which have no tilt angles, while the opposite is true for clearance ring cutters which are progressively tilted towards the face side of drum to overcome adverse corner cutting conditions. Axes of tools without tilt angles, for example the vane picks, are in line with the direction of their trajectories, i.e. both the tool axis and tool trajectory lie on the same plane, if skew angle is zero (Figure 4). With tilted picks, both the tool axis and tool trajectory, however, no longer lie on the same plane, and the tool axes are tangential to the trajectories. It is interesting to note that a skew angle between tool axis and cutting trajectory is, to a certain value, always inherent in the tilted picks, owing to this tangential position. Details of tool rotation related to tilted picks will be discussed in the next section, since they are overwhelmingly employed on roadheaders cutting heads.

The rotational motion of point attack picks without skew angle as observed with drum shearers during the practical trials, probably results from the effect of a rotative force generated at rock-tool interface. The sideway force, among the all components of the resultant tool force, may probably be the source of such rotary action which generates a torque for tool rotation. Identifying the circumstances under which sideway forces are present is, therefore, a very important point in this respect. In tool lacing, the pick cutters are staggered to form helical vanes (starts or cutting sequences) to avoid simultaneous pick loading. During actual cutting operations, the locus of the tip of adjoining picks in a given cutting sequence describes a line known as cutting perimeter which is always inclined with an angle (β) to the horizontal axis (Figure 5). The angle of inclination for the vane picks of drum shearers and continuous miners arranged in single-tracking and multi-tracking lacing may, then, be expressed as follows, provided that both the cut spacing (S_C) and circumferential pick spacing (θ) are constant:

$$\beta = tan^{-1}\left[\frac{\theta A}{360\ S_C}\right] \tag{2}$$

where β = Angle of inclination (degree), θ = Circumferential pick spacing between the adjacent tools of the same sequence (degree), A = Advance per revolution of the cutting head (mm) and S_C = Original spacing (or cut spacing) between the adjacent tools of the same sequence (mm).

Previous laboratory linear cutting research with heavy-duty point attack picks on simulation of the vane picks of a two-start drum with one tool per line (single tracking) revealed

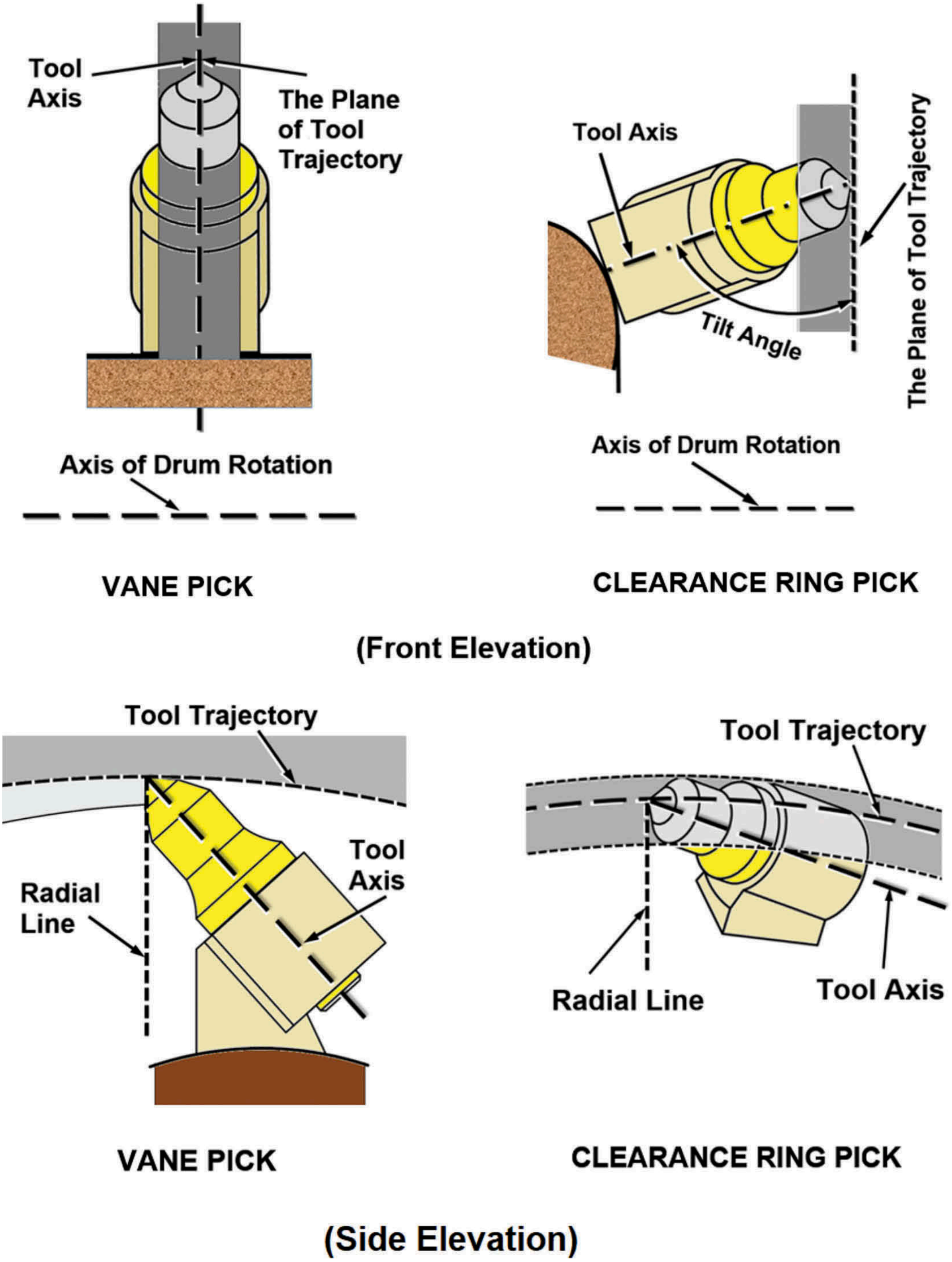


Figure 4. Cutting positions of a vane pick and a clearance ring pick on a cutting drum.

that the values of tool forces and specific energy were significantly affected by the angle of inclination β [12]. It was stated that the sideway force diminished to zero, while the cutting and normal forces exhibited minimum values at 10° angle of inclination. This finding was also confirmed by additional laboratory studies on a three-start drum with one tool per line

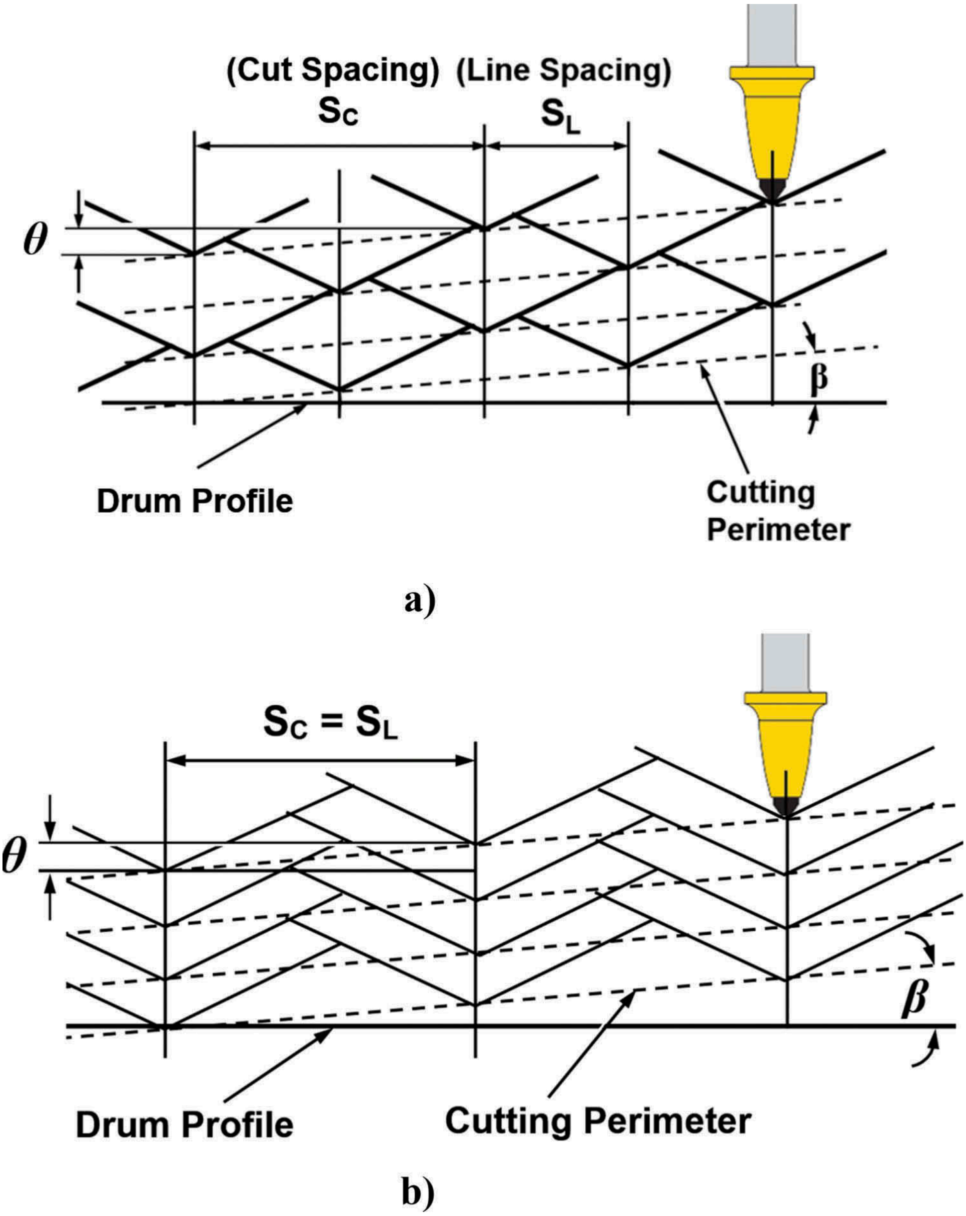


Figure 5. Depiction of angle of inclination (*β*) during actual cutting action; with (a) single-tracking drums and (b) multi-tracking drums.

arrangement [13]. All these laboratory findings indicated that sideway forces are generated when both sides of the groove formed by a given tool pose an asymmetrical profile. It was also inferred that sideway forces do not tend to occur if the groove profile is symmetrical. It, then, emerges to be important to define the angle of inclination whether it corresponds symmetrical or asymmetrical position for a given condition, since it has pronounced effect on the presence of sideway forces. The angle of inclination at a position of symmetry for the vane picks of shearer drums, together with the line tools of continuous miners, laced in one tool per line or single tracking, may be expressed in terms of line spacing S_C as follows:

For a two-start lacing:

$$\beta_S = tan^{-1}\left[\frac{A}{3S_C}\right] \tag{3}$$

For a three-start lacing:

$$\beta_S = tan^{-1}\left[\frac{A}{5\ S_C}\right] \tag{4}$$

It is important to note that drum shearers with multi-tracking lacing have still been considerably employed in practice, despite their disadvantageous performance over single tracking lacing. The manufacturers' drums mentioned in this paper were also designed with multi-tracking lacing. Similar expressions related to drums with multi-tracking lacing are also given, as follows:
For two-start with 2 tools per line:

$$\beta_S = tan^{-1}\left[\frac{A}{4\ S_C}\right] \tag{5}$$

For three-start with 3 tools per line:

$$\beta_S = tan^{-1}\left[\frac{A}{6\ S_C}\right] \tag{6}$$

In considerations with the above-mentioned explanations, the condition of '$\beta \neq \beta_S$' should, therefore, be satisfied for asymmetrical cutting positions where sideway forces are generated. For this reason, the angle of inclination obtained from Equation (1) for a given drum conditions needs to be checked with those of Equations (3,4,5 and 6), i.e. to find out whether the calculated angle of inclination is symmetrical or not. It may be seen that the advance per revolution together with cut spacing are the common parameters included in the Equation (2) and in the Equations (3,4,5 and 6), but circumferential pick spacing, θ, which only exist in the Equation (2). The advance per revolution, A, is not always constant, since it is subjected to change during cutting operations, due to varying face and operating conditions. This situation does, however, not affect '$\beta \neq \beta_S$' condition, as any change in A will be reflected with the same proportions for all equations. Furthermore, both θ and S_C are constant for a given drum, since they are set during lacing stage. The cut spacing is defined in accordance with 'spacing to depth ratio' where depth is dictated by A. By virtue of the value of A, the setting values of S_C is usually between 50 to 90 mm depending upon lacing pattern, whereas θ is independent from A, and its values range between 90° and over 270°. The change in the values of S_C is, therefore, not significant compared to that of θ. It then emerges to be important to understand the factors affecting the value of θ.

The θ increases with an increase in angle of wraps for a given drum condition. The angle of wrap is usually considered for optimum loading conditions of drum shearers along with parameters such as drum width, drum diameter, rotational speed of drum, haulage speed, vane angle, and so on [14]. With conventional drum shearers, the maximum drum speed is in excess of 40 rpm and the maximum haulage speed is around 6.0 m/min. Drum diameters can go up to 3.0 m, whilst drum widths can hardly exceed 1.0 m. Under such circumstances, higher angle of wraps is the case with large-diameter drums, whereas the opposite is true for drums of smaller diameters, depending upon the number of helical vanes. With the last generation shearers, the haulage speed, however, tripled those of conventional shearers, which consequently resulted in increase in drum speeds. There have, however, been no significant changes in drum lacing pattern and drum dimensions, in spite of increases in both haulage speed and drum revolutions with the latest drums. The factors affecting the angle of inclination, hence, virtually remain unchanged, i.e. θ is still significant parameter for both conventional and last generation drums.

The above-mentioned advance per revolution ‘A’, corresponds the maximum depth of cut (d_{max}) taken by a pick for a given condition. This depth of cut is generally constant for machines performing helical motion, while it continuously changes with cycloidal motion. Drum shearers typically perform cycloidal motion where the depth of cut per pick continuously varies with angular position of tools in a given cut sector. The instantaneous depth of cut for a given angular position for cycloidal motions is expressed, as follows, provided that the radius of cutting is much more greater than advance per revolution [15]:

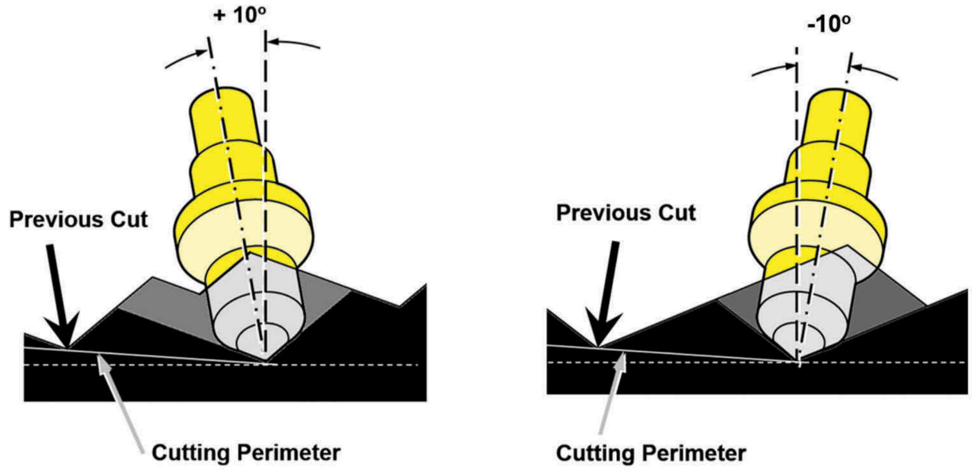
$$d = d_{max} \sin \alpha \tag{7}$$

where d = Instantaneous depth of cut (mm), d_{max} = Maximum depth of cut which is equal to the value of A (mm) and α = Angular position of a given tool (degree).

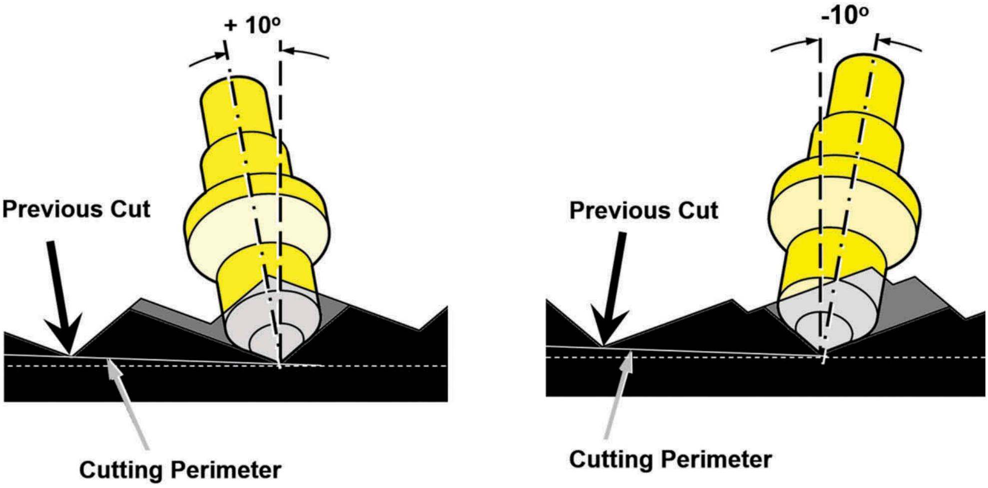
The Equation (7) indicates that angle of inclinations calculated by Equations (2,3,4,5 and 6) are bound to change continuously due to the continuous variations in A. This situation does, however, not affect the ‘$\beta \neq \beta_S$’ condition, since any change in A will be proportionally reflected in the respective values of angle of inclinations.

The aspects of symmetry in the angle of inclination for a given drum condition needs to be checked to seek the possibility of tool rotation. The results of in situ trials described in this study may be used to verify the tool rotation in considerations with the equations given above. The specifications of drums and operating conditions are presented in Table 1. The β_S values were obtained from Equations (4) and (6), respectively. It is seen that the angle of inclination calculated by the Equation (2) is different from those at the symmetrical position, i.e. the ‘$\beta \neq \beta_S$’ condition is satisfied for both drum conditions. This analysis supports the view that tool rotation occurring at zero skew angle is due to the presence of sideway forces which result from position of asymmetry determined by the equations derived in this study.

Previous laboratory study suggested that a positive skew angle is more advantageous as to cutting efficiency and structural stability of point attack picks [10]. This was ascribed to the differences between the surface area covered by tool tip and tool neck contacting the rock. It was stated that with negative skew angle this area is larger than that of positive skew angle. It is important to note that these laboratory experiments were carried out at shallow depth of cuts along a horizontal line, being 6 mm, which is well below those of drum shearers. Furthermore, the relative cutting positions of adjacent tools may not be as in laboratory conditions, since this line is always inclined rather than being horizontal, as in Figure 5. Moreover, under such laboratory conditions it is rather convenient to identify whether the skew angle is positive or negative, while the opposite is not always true for actual cutting conditions, due to changes in the effective values of depth and spacing. The maximum depth of cut at normal operating conditions observed with the drum shearers described in the present study was between 20 and 30 mm. The groove profiles of a vane pick at 30 and 15 mm theoretical depths are illustrated for both single tracking and multi-tracking lacings at +10° and −10° skewed positions, respectively, as in Figure 6. It, then, appears that there is no significant differences between the respective contact areas covering tool tip and tool neck at +10° and −10° skewed positions, since the contact areas overwhelmingly remain within the cross-sections of the groove to be cut by the given pick, particularly with single tracking lacing. Such a difference may, however, be distinct at very shallow depths which occur at lower cut sectors or lower angular positions in a cycloidal motion. Even under such a circumstance, the effect of skew angle may not be very significant in terms of the contact area and contact position, owing to the magnitude of tool forces which is generally very low when cutting coal at such shallow depths. This phenomenon may also infer that in cycloidal motion the influence of sideway forces on tool rotation is more effective at higher angular positions of the picks.



SINGLE TRACKING AT 30 MM DEPTH OF CUT

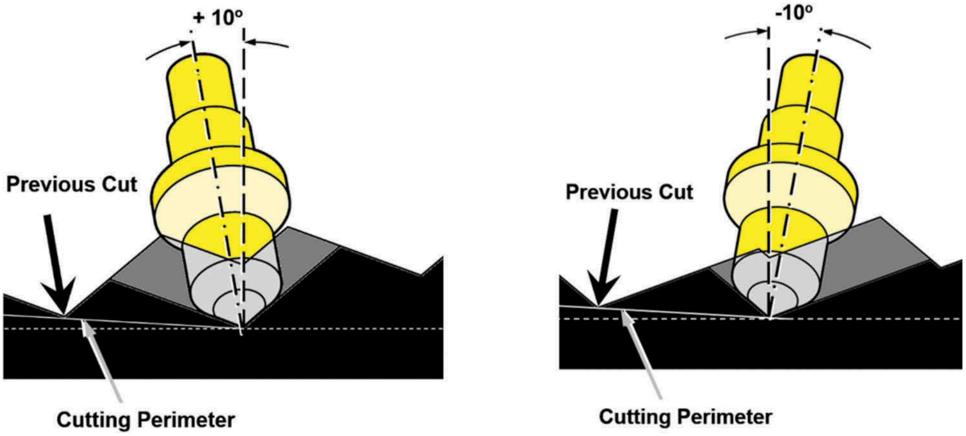


SINGLE TRACKING AT 15 MM DEPTH OF CUT

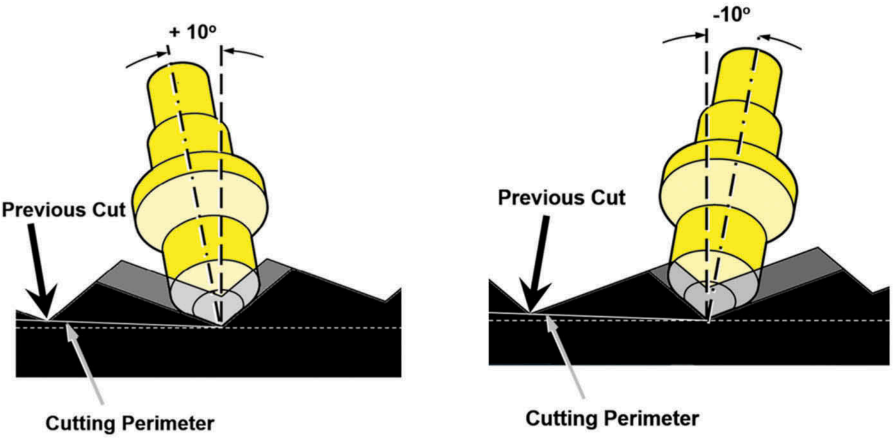
Figure 6. Conceptual drawings of the groove profiles of a vane pick at 30 mm and 15 mm theoretical depths for single tracking and multi tracking lacings at +10° and −10° skewed positions, respectively.

Previous laboratory investigations also reported that more heat is generated at the tip of larger diameters tools when the pick is skewed [8,9]. Temperature increase at the pick tip is inevitably disadvantageous, as it aggravates the problem of ignition sparking of methane in coal mines. Moreover, coals are generally non-abrasive materials by nature, and tool wear with coal cutting picks is mainly due to the heat built-up at the pick tip owing to friction between the tool and the coal. The skew angle may, therefore, not be very useful in terms of frictional ignition and tool wear.

With special considerations to the results of aforementioned practical and laboratory investigations, it may be reasonable to put forward that point attack tools are able to rotate successfully without skew angles on drum shearers and continuous miners, and this arrangement may be advantageous for extraction of coal materials particularly when operating in potentially explosion hazard conditions.



MULTI TRACKING AT 30 MM DEPTH OF CUT



MULTI TRACKING AT 15 MM DEPTH OF CUT

Figure 6. (Continued).

3.2. On tool rotation with roadheaders

The tool lacing of roadheaders is, to a greater extent, different from those of drum type mechanical miners. In contrast to drum shearers and continuous miners, the tools fitted on roadheaders are overwhelmingly arranged with tilt angles. The last generation roadheaders, whether axial or transverse type, predominantly employ cutting heads of conical geometry where nearly the all tools are arranged with tilt angles. The condition of zero-degree skew angle is, therefore, not the case with roadheaders, since a skew angle is always inevitable with tilted tools, as illustrated in Figure 4. Under such circumstances, the value of skew angles depends upon two major parameters; the cutting radius of tool, and the position of the radial line which projects from the centre of cutting head rotation with respect to the line of tool axis. These results can be evaluated as follows in order to bring a conclusive understanding in tool rotation:

Setting I: Tool rotation may be attributed to the inherently existing skew angles, whilst tool holder damage may be due to friction with rock materials. This situation may be explained better if the relative position of picks and tool holders are considered with respect to the path of the trajectory described by a given pick during cutting motion, as depicted in the Figure 3(a). It was thought that the path of the trajectory provides a protective shield for part of a tool holder in proximity of this path. Under this condition, the upper portion of the tool holder emerges to be more prone to friction with rock material, since it poses the closest projection to the pick tip due to the angle of attack. It may be seen that the left hand side of the tool holder, particularly the part marked by thick arrow in the Figure 3(a), is far from the path, and exposed to rock material. This was probably the reason for the wear observed with the left side of these tool holders.

Setting II: The occurrence of rapid failure might be ascribed to the altered position of tool holders where the left part of them was shifted further away from the tool trajectory than that of setting I Figure 3(b).

Setting III: Shank breakage was probably due to the generation of high asymmetrical forces arising from the hard siliceous inclusions. The best performance gained from this setting with large-diameter point attack picks among all, may be attributed to the fact that the part of the tool holders which is prone to damage as marked by thick arrow in Figure 3(c) was much closer to the cutting trajectory than the other two settings. This vulnerable point was farthest with the Setting II. The shank breakage implies that the asymmetrical pick forces acting on nose picks are greater than those of other picks on the cutting head. This result, thereby, infers that point attack picks with small shank diameters may not be suitable for the nose portion of roadheaders cutting heads. The value of tool plan length *l*, may, however, be considered as half the plan length of pick gauge to avoid shank breakage, in conditions where point attack picks with small shank diameters are to be employed. With this arrangement shank breakage might be alleviated, whereas tool-holder damage will still be the case, though not so severe as that occurred with the settings I and II.

The tool holder damage observed with the nose picks of the cutting head may also be related to the friction of tool holders with uncut ribs between the adjacent grooves, along with the friction with the cut materials. The picks located at the nose portion of the cutting heads are affected most by such friction. It would be better to examine the tool positions on axial and transverse cutting heads, respectively, in order to explain this situation. Cutting positions of roadheaders cutting heads for an advance per revolution when arcing left or right are depicted in Figure 7. It may be seen that at the nose portion, the area swept per revolution is much higher with transverse cutting heads than that of axial types. Under such conditions, the nose picks of transverse cutting heads are much more vulnerable to damage, due to increased amount of cut material and presence of higher uncut ribs. Moreover, the trajectory of nose picks also imposes an effect on the values of skew angles. When arcing, the picks on transverse cutting heads follow a circular path, while those of axial heads describe a cycloidal path. The '*x, y*' coordinates of a point on the trajectory of a cycloidal motion in an up-milling cutting mode which is usually practised by roadheaders are given as follows [16]:

$$x = A(\alpha/360) + R\sin\alpha \tag{8}$$

$$y = R(l - \cos\alpha) \tag{9}$$

where: A = Advance per revolution (mm), α = Angular position in a cut sector (degree) and R = Cutting Radius (mm).

By virtue of this situation, the nose picks describing cycloidal motion will have different skewed position from those having circular motion. The difference between these motion is very distinct for the corner picks at the front most line of the cutting head at higher advance per revolutions, e.g. at a practical value of 140 mm/revolution when cutting soft materials. When cutting medium-strength rock materials, the advance per revolution observed in practice by the author is around 30 and 50 mm with axial heads, whilst being less than this value with transverse

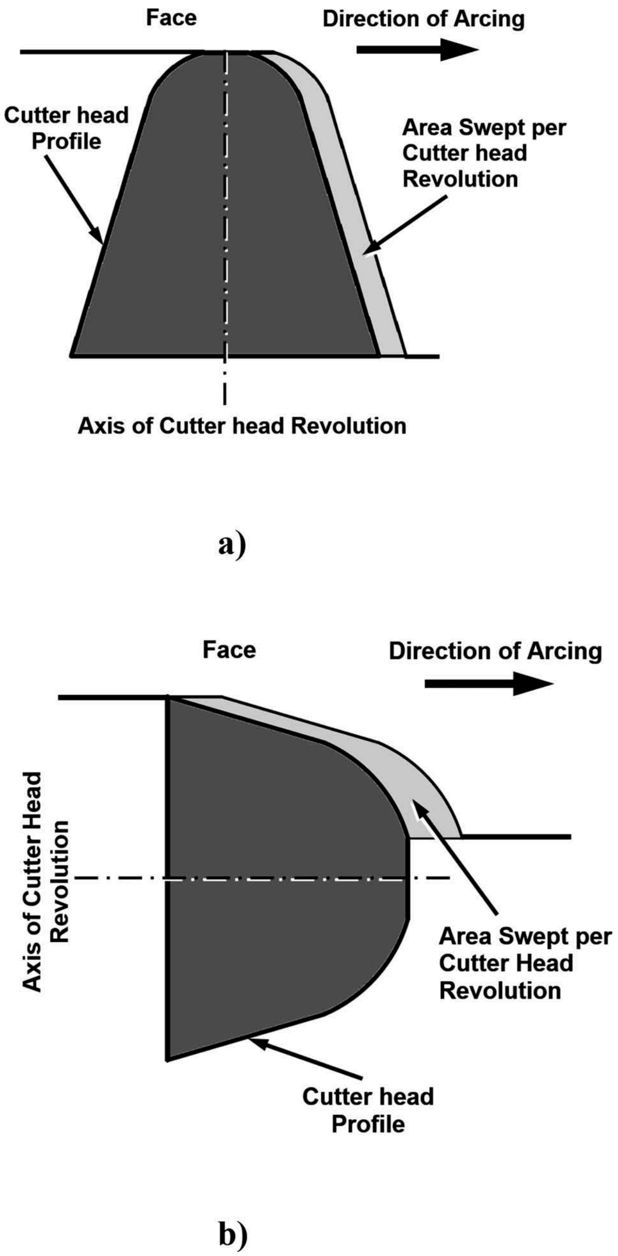


Figure 7. Cutting positions of roadheaders for an advance per revolution when arcing; (a) axial type cutting heads (b) transverse type cutting heads.

heads. Within this range, the trajectories of axial heads are in close proximity to those of transverse heads, if these practical values are considered in the above equations. This situation is, however, different when cutting soft rocks at higher advance per revolutions, e.g. at a practical value of 140 mm which was observed during these trials, as depicted in Figure 8, for skew angles at Setting I and Setting III, respectively. It may be seen that the distance between the vulnerable part of the tool holders and the outer boundary of the tool tip trajectory tends to rise as the angular position increases, i.e. the area exposed to uncut ribs and cut material increases for the both cases. This is, however, much more distinct with zero skew angle Setting I, hence indicating

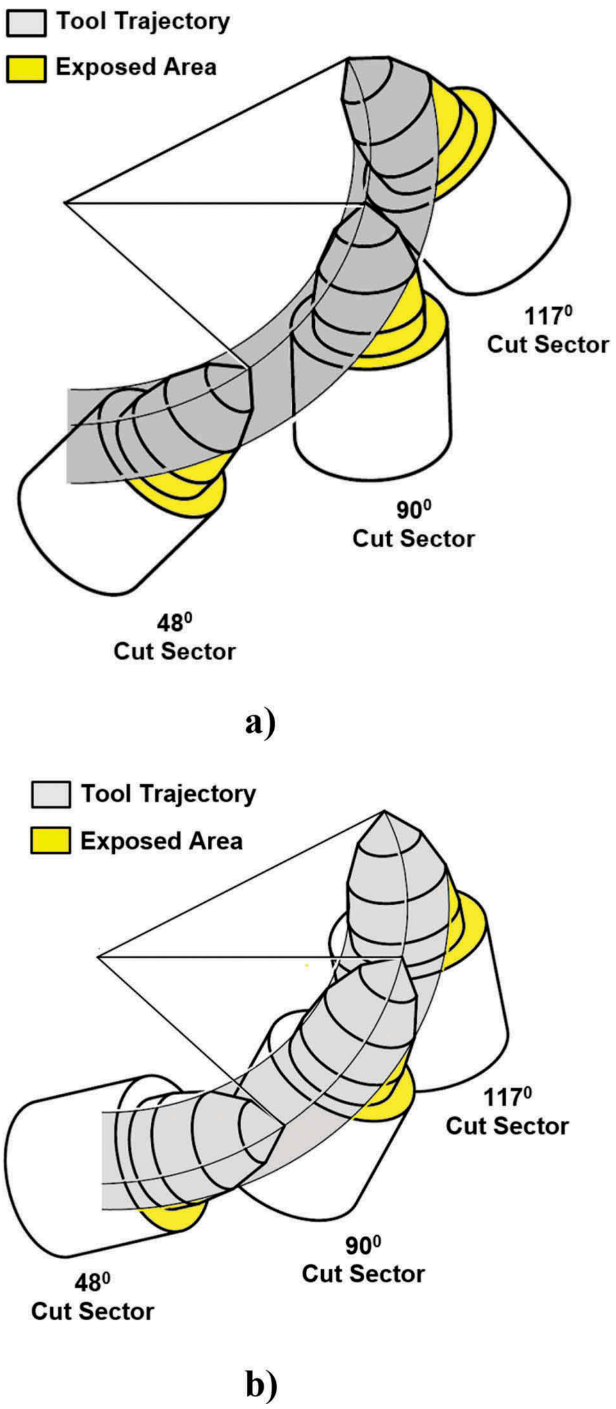


Figure 8. Skew angles for various cutting sectors in cycloidal motion; (a) at Setting-I, (b) at Setting-III.

the superiority of the Setting III suggested in this study. This situation also implies that more tool holder damage would be the case towards 180° cut sectors. At the other end, the cutting vibration is known to be more balanced at higher values of cut sectors, provided that no groups of picks perform simultaneous cutting, i.e. machine balance generally improves towards 180° cut sector. It should be noted that cutting at full 180° cut sector usually takes place during initial sumping action when in arcing and/or lifting. Beyond that, transverse cutting heads do not generally exceed 90 cut sector, whilst axial types can operate well above this value. The transverse type cutting heads are not influenced by the adverse effect of cycloidal action in any rock type, since they overwhelmingly perform helical motion. The opposite is, however, true for axial type cutting heads particularly when cutting relatively soft materials.

Setting the skew angles either in positive or negative position is rather a difficult issue with roadheaders cutting heads, due to complex characteristics of tool lacing, in particular with tilted tools which constitute great portion of total picks fitted. By definition, the skew angle is said to be positive if tool axis is skewed towards relieved side of the cutting sequence, while it is negative if the tool axis is offset vice versa. In actual cutting conditions, it is not always easy to distinguish this feature with roadheaders. First of all, the line described by the tips of adjacent tools of a given sequence is always in the form of a curve rather than a straight line. Second, the area swept by the adjacent tools are not always consistent. Moreover, the progress of cutting sequences, e.g. whether the cutting progressively start from the nose portion to the rear or vice versa, is another factor in this argument. Roadheaders cutting heads are, however, designed in such a way that cutting begins from the nose of the cutting head and then progresses towards the machine side to assist clearing the cut material. Under such conditions, with the setting II the skew angle appears to be positive, while it is negative with the setting III, since these two settings are arranged in opposite manner. It, then, emerges that setting the skew angles in positive is not advantageous with roadheaders, since the worst performance was obtained from the setting II among the all settings investigated.

It may be concluded that with the roadheaders, regardless of the cutting head type, a skew angle in accordance with the Equation (1) may be recommended for large-diameter point attack picks.

4. Conclusions

A number of long-term underground investigations were performed with drum shearers and roadheaders. Trials with drum shearers took place at two different coal mines with different types of shearers. In each mine, drums of two different lacings were investigated with slender type and large-diameter type point attack picks, respectively. Three different types of skew angles were investigated with light duty and medium duty axial type roadheaders fitted with slender type and heavy duty type point attack picks, respectively. The all trials indicated that point attack picks have to be provided with optimum cutting positions in an effort to achieve rotary action in their tool holders which is a must for these types of tools. A number of formulas were derived to define optimum conditions for tool rotation.

Based upon the findings of these investigations, following conclusions may be drawn:

(1) With drum shearers and continuous miners:
  - Point attack picks were found to rotate in their holders without introducing any skew angles, provided that the machine and operational parameters are verified in considerations with the equations given in this paper.
  - Skew angles may not be advantageous when operating in potentially explosion hazard conditions.
  - Setting the skew angles in negative or positive manner may not be significantly beneficial.

(2) With roadheaders:
  - Cutter tools with tilt angles are always subject to the effects of intrinsically exist skew angles, and the values of these angles were found to be critically affected by the radial line position with respect to the tool axis.

- Skew angles calculated for each tilted pick separately by Equation (1) may be recommended for roadheaders, and this is typically a negative skew angle which ranges from 0° up to 30° depending upon cutting radius of the pick.
- With positive skew angle, heavy tool holder damage and tool shank breakage were observed.
- Small diameter picks may not be suitable for the nose portion of the cutting heads.

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Disclosure statement

No potential conflict of interest was reported by the author.

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