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Influence of cutting parameters on the performance of plough during hard rock cutting in coal mining

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Abstract

Coal ploughs have proved very successful on many faces in various parts of the world. Recently, there has been a general tendency in longwall working to increase the speed at which the machine progresses along the coal face. An increase in production rate demands enhances either due to depth of penetration or cutting speed. This, in turn, results in increasing power demand and also the force acting on an individual pick. To get maximum efficiency from a cutting machine, a number of parameters need to be investigated. The first and foremost thing of interest is naturally the pick geometry. The cutting force can be expected to depend mainly on the rack angle and clearance angle of the tool. The second parameter is the cutting depth, which when enhanced, increases the rate of advancement and, at the same time, results in enhanced cutting force. This results in large power demand and increases wear of picks. Thirdly, cutting speed, in which higher cutting speed will increase the production rate but at the same time is expected to enhance the power demand and the cutting force. This paper aims at investigating the cutting efficiency of the plough by simulating the coal cutting operation in the laboratory. The effect of three main parameters like pick geometry, cutting depth, and cutting speed, on cutting efficiency have been studied in detail. The cutting force elevates at a faster rate with an increase in depth at higher speeds. The percentage increase in force is nearly 20% for a speed increase of 20%.

Keywords

pick geometry, cutting depth, cutting speed, coal mining, plough

RESEARCH ARTICLE

Influence of cutting parameters on the performance of plough during hard rock cutting in coal mining

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Abstract

Coal ploughs have proved very successful on many faces in various parts of the world. Recently, there has been a general tendency in longwall working to increase the speed at which the machine progresses along the coal face. An increase in production rate demands enhances either due to depth of penetration or cutting speed. This, in turn, results in increasing power demand and also the force acting on an individual pick. To get maximum efficiency from a cutting machine, a number of parameters need to be investigated. The first and foremost thing of interest is naturally the pick geometry. The cutting force can be expected to depend mainly on the rack angle and clearance angle of the tool. The second parameter is the cutting depth, which when enhanced, increases the rate of advancement and, at the same time, results in enhanced cutting force. This results in large power demand and increases wear of picks. Thirdly, cutting speed, in which higher cutting speed will increase the production rate but at the same time is expected to enhance the power demand and the cutting force. This paper aims at investigating the cutting efficiency of the plough by simulating the coal cutting operation in the laboratory. The effect of three main parameters like pick geometry, cutting depth, and cutting speed, on cutting efficiency have been studied in detail. The cutting force elevates at a faster rate with an increase in depth at higher speeds. The percentage increase in force is nearly 20% for a speed increase of 20%.

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1. Introduction

Mainly, "rock cutting theories are based on the assumption of either tensile or shear type failure of the rock. It is commonly accepted and proved that, when mechanically excavated, rocks can be cut most efficiently by picks which have large rake angles" [1–4]. Therefore, with the exception of high-strength rocks, it is generally desirable to have as higher rake angle as possible. In high-strength rocks, the risk of cutter picks damage increases with increasing rake angle [1,5,6]. Therefore, when cutting this type of rock, low or negative rake angles are a necessity. One of the most fundamental rocks cutting theories was proposed by Evans [1]. Evans's model of tensile breakage describes the wedge penetrations into a buttock of coal. The theory gives an estimate of the cutting force (F) on a wedge as given in equation (1).

$$F = \frac{td\sin(x)}{\sin(y)\cos(x+y)} \tag{1}$$

where x is the half wedge angle, t is the tensile strength of the rock, d is the cutting depth, and y is the angle between the cutting direction and the line along which the tension crack propagates. The theory predicts that likely tensile-type failure cannot be maintained for the rake angles of less than approximately 5–10° [7,8].

Another rock cutting theory has been developed by Nishimatsu, who used the Mohr-Coulomb criterion of failure for the stress condition during the formation of a chip. Shear strength is an important

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parameter which assists in predicting the required cutting force [9]. It has also been predicted that shear-type failure is valid up to the negative rake angle values of −15° to −20°. The experimental verification of the theories has made it clear that tensile-type failure is not likely to be valid when cutting high-strength rocks at negative rake angles [10,11]. Cutting machine picks have cutting tips composed of tungsten carbide brazed or pressed into a steel supporting body. The steel body can be subdivided into two zones, the shank, which fits into the pick holder, and the pick body, which projects beyond the holder. There are three styles of pick in general use; radial, forward attack, and point attack [12,13]. Radial attacks comprise shanks equal to the varied ways [1,14,15]. On the other hand, the shank of forward attack picks is angled backward from the cutting direction, usually at about 45°. Both of these picks use “wedge” tips. Point attack picks are essentially forward attack picks with conical shapes rather than wedge-shaped tips. Most of the investigators tend to believe that the radial bits are more energy efficient than conical bits, however, they are more easily affected by wear [16]. Hence, experimental work is limited to radial-type picks [17]. In terms of gas production, coal reserves are crucial. The permeability of coal beds is a key element in determining whether gas can be extracted. Previous research on the porosity and compressibility of coal has been widely disseminated. All previous experimental work ran into the same problems, including: (1) acquiring well-cleated, proficient samples; (2) developing sample preparation techniques that did not harm coal samples; (3) equipment constraints that dictated the use of experimental stress regimes not representative of in-situ coals; and (4) extreme hysteresis, preventing replication of results from a sample [18].

An increase in the depth of cut decreases the specific work done (work done per unit weight of coal produced). In other words, there is a rapid increase in efficiency with increasing depth of cut. Physically, some of the important interpretations are (i) at shallow depth, the process resembles a grinding action that utilizes a large proportion of energy in producing fines and overcoming friction; and (ii) at deeper depth, there is a greater degree of splitting induced by the picks and a rapid increase in the quantity of coal with proportionately less energy utilized in crushing. Cutting force for both the picks enhances linearly with increasing depth of cut, and in general, there is a direct proportionality [19]. A striking finding is that changes in cutting speed had no effect on mean cutting force. The explanation of this important result mainly lies in the speed at which tensile crack propagates through the coal during the process of chip formation. If the speed of crack propagation is much greater than the pick speed, it is reasonable to expect that changes in pick speed would not modify the breakage process appreciably. Specific work done is also more or less unaffected by the variation in cutting speed. If the coal is friable, the weight of the coal cut shows an increasing trend due to the impact of the pick at higher speeds [19]. In general, clearance angles greater than +5° have no effect on forces. As the cutting process continues, all bits develop an initial large wear angle (15°) on the wear flat, which gradually stabilizes at 1–10°, depending on the hardness of the rock and bit tip. From 0° clearance angle to approximately 5° angle, the ploughing resistance decreases with increasing clearance angle. If the clearance angle is kept large, wear on the free surface decreases. Similarly, at the same working conditions, the tip strength also decreases at the same time. From all the previous research that had been carried out, it is evident that the best clearance angle is approximately 6°. In general, the ploughing resistance decreases with increasing rake angle. Provided that the tip of the bit is strong enough, it is advisable to have a large rake angle [20].

To date, there has been relatively limited research on the cutting efficiency of plough and expanding their usage to break tougher rock and coal formations. Laboratory-scale experimental design was not found elsewhere in the literature related to the simulation of coal-cutting operations. This paper aims to investigate of cutting efficiency of the plough by simulating the coal-cutting operation in the laboratory. The effect of three main parameters like pick geometry, cutting depth, and cutting speed, on cutting efficiency has been studied in detail.

2. Experimental setup

The experimental simulation consists of a grooving tool in which a single pick plough is used to make a groove in a coal block, as shown in Fig. 1.

2.1. Cutting pick

Three picks were prepared from lathe machine cutting tools. The material of the tool was high-speed steel. The picks were given the desired shape on an angular grinding machine. The clearance angles of the picks were 5°, 10°, and 15°. The rake angle for all three was kept at 13°. In the later part of the work, the rake angles of the picks were changed

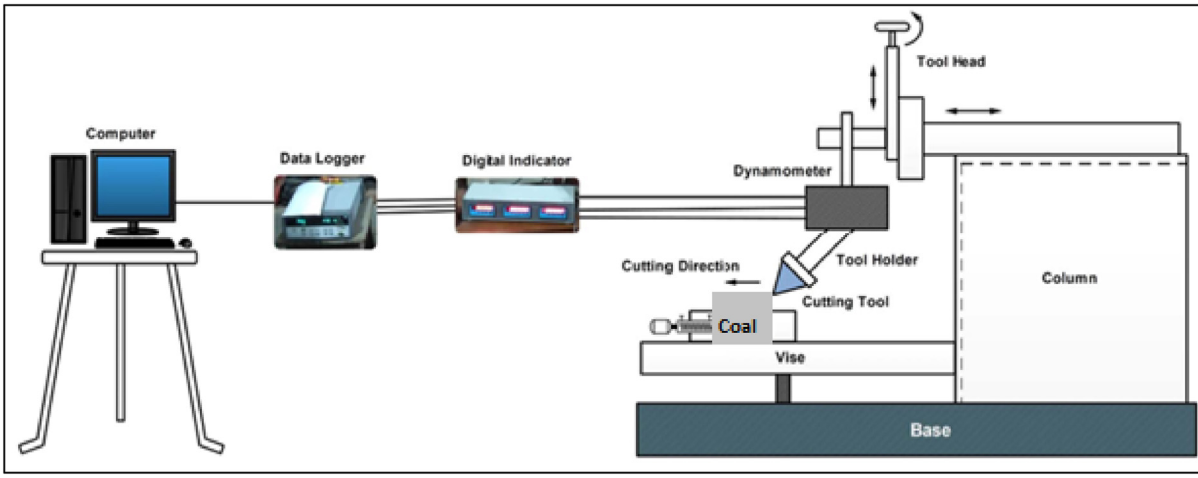

Fig. 1. Experimental simulation on a laboratory scale.

to 17°, 20°, and 25°. The side clearance angle was kept fixed for each pick i.e., 6°.

2.2. Tool holder

A 10 mm steel plate of length 90 mm was taken and grooved in the center. Afterwards, the plate was cut into two halves, and the two pieces were welded together to give a holder having an 11 mm square hole. Two screw grooves and their in-fitting screws were made to clamp the tool properly inside the holder.

2.3. Shaft with strain gauge

A steel shaft of 21 mm × 21 mm in dimension was taken and welded to the holder. However, the 2-inch length of the shaft was thinned to a dimension of 21 mm × 10 mm. A pair of strain gauges were fixed on this thinned portion of the shaft. This shaft thinning was done to increase the sensitivity of the strain gauge. At the same time, it was ensured by assuming a maximum load of 50 kg while cutting. It was concluded that the shaft was strong enough to bear the strain. The strain gauge resistance was 120 Ω, and it was fixed on two thinned sides of the shaft with the strain indicator.

2.4. Strain indicator

The strain gauges were connected to a strain indicator in a half-bridge connection. The strain gauges were calibrated, and strain indicator readings were noted. Actually, there are two forces (i.e., horizontal cutting force and transverse force on the tool tip) acting on the pick while cutting the coal. To nullify the effect of transverse force on the shaft's bending, the tool tip was placed so as to align it to the shaft axis. Thus, the strain indicator gives the measurement of horizontal force only.

2.5. Casted coal blocks

Coal is a brittle material, and it was very likely that a moving pick would have shattered the sample. To avoid this, coal was casted in concrete. This casting was also helpful in holding the sample. Coal blocks of approximately 6-inch × 6-inch × 6-inch in size were cut. They were placed in a wooden box of size 8-inch × 8-inch × 3-inch. The remaining space inside the box was filled with concrete. The concrete mixture mainly consists of stone chips, sand, cement, and water. The projection of coal above the cast was around 3 inches.

3. Experimental procedure

The stroke length and speed of the shaping machine were fixed. The stroke length was kept around 12 inches, and the machine speed was kept at 0.12 m/s. The plough was fixed in the holder of the machine and tightened properly. The bit selected had a rake angle of 13° and a clearance angle of 5°. The coal block was placed on the platform of the shaping machine and fixed rigidly. Some plough runs were made with small cutting depths to smoothen the coal surface and level it properly. The cutting depth was fixed at 0.6 mm. The strain gauges were connected to the strain indicator as described before. A clean cloth was spread in front of the plough to collect the cut coal. The machine was started, and the eyes were continuously monitored by the strain indicator. The maximum reading was noted. Five such runs were made, and recorded the readings. The cut coal was collected in a polythene bag which was given a number for identification. The above steps 1 to 10 were repeated for three more cutting depths, i.e., 1.2 mm, 1.8 mm and 2.1 mm. The machine speed was also varied between 0.24 m/s and 0.43 m/s, and the above steps 1 to 11 were repeated for each of them. Similarly, a new tool was fitted with the same rake angle and clearance angle of 10° and 15°. All the above steps were repeated. As explained earlier, the rake angles of the three tools were changed to 17°, 20°, and 25°. Once again, all the steps from 1 to 12 were repeated for the three tools. The cutting depth was taken only to be 0.6 mm and 1.2 mm. This was done to weaken the tool tip by increasing the rake angle.

4. Result and discussions

4.1. Determination of cutting forces

From Figs. 2–4, the cutting force observed on the tool tip has been found to increase linearly with cutting depth. The key drawbacks of experimental research include the inability to go to much greater levels due to force escalation. Similarly, the force has been found to enhance with a gradual increase in machine speed. Almost all the researchers have postulated that variation in speed does not cause any appreciable change in the cutting force. This discrepancy may be explained by the fact that almost all the works were carried with a large range of speed compared to this work. All the plots of force versus speed show a trend of getting flattened at higher speeds. This, in a way, agrees with the earlier findings.

At a very low cutting depth (0.6 mm), the tendency of flattening is not found. Thus, low cutting depth may become the main deciding factor about the force. At large depths, the force is found to be very high, and change in speed has very little effect compared to the magnitude of forces. The cutting force was found to remain constant with changes in the clearance angle of the tool. The maximum variation found was not more than 10%. Hence, it is desirable to keep the clearance angle near 5°, increasing above which will only weaken the tool and nothing else. From Figs. 5 and 6, the force has been found to decrease hyperbolically with increasing rake angle. However, the increase in the rake angle decreases the wedge angle and hence the result. This fact cannot be used as a major advantage in which strength consideration of the tool limits the wedge angle to 50–60°.

4.2. Determination of specific energy

Specific energy is defined as the amount of work required to produce a unit mass of coal. It was calculated and plotted against cutting depth, cutting speed, and rake angle. Specific energy shows a

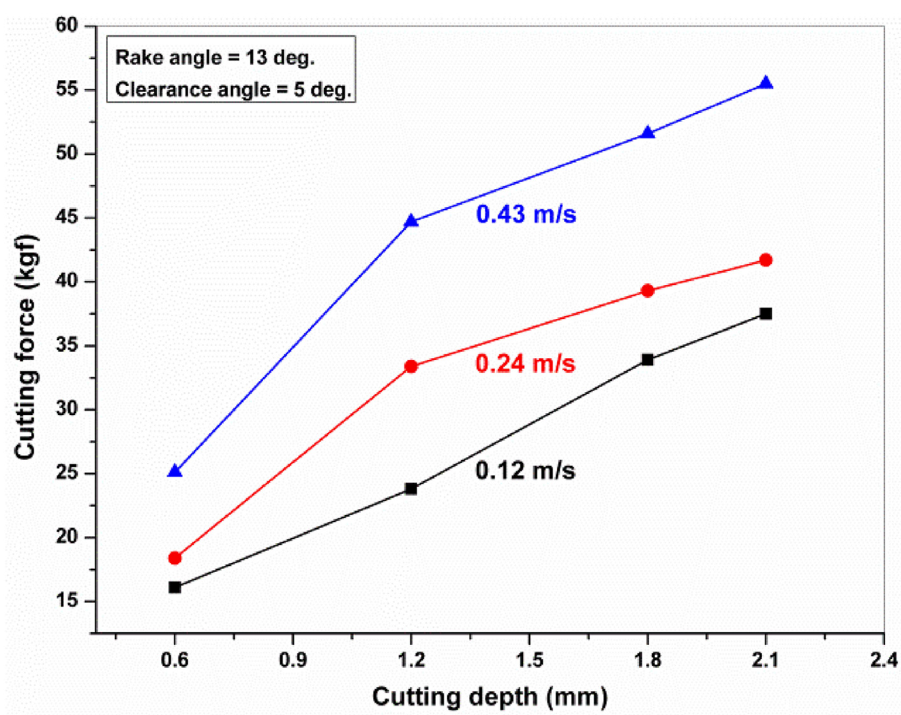

Fig. 2. Determination of cutting forces for different depths and varying speed with a clearance angle of 5°.

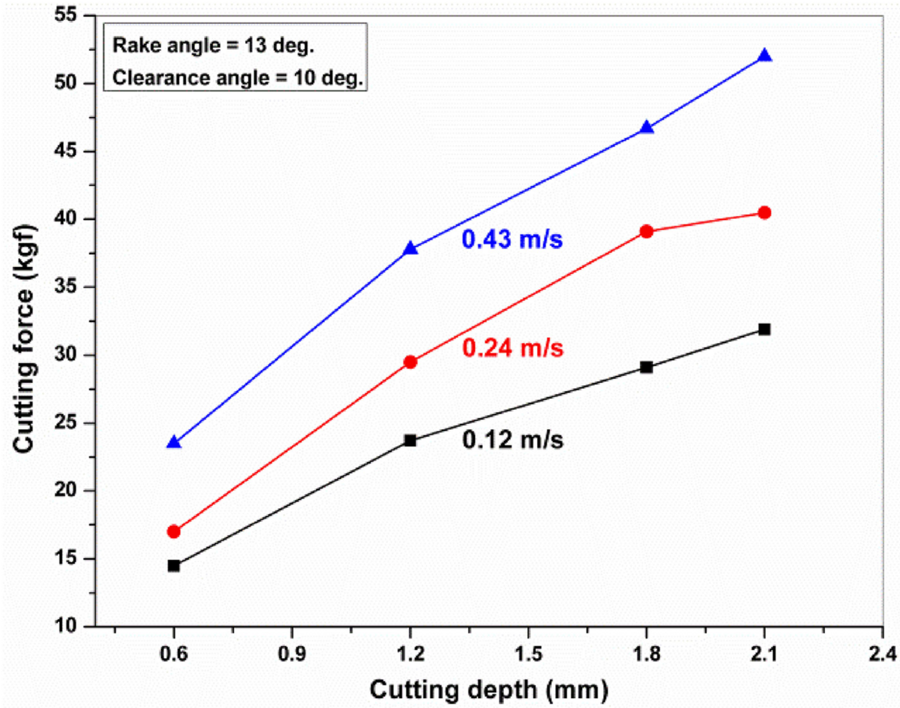

Fig. 3. Determination of cutting forces for different depths and varying speed with a clearance angle of 10°.

decreasing trend with an increase in cutting depth, as depicted in Fig. 7.

This can be expected as a large amount of energy is wasted in grinding action at lower depths [21,22]. With increasing speed, due to large power requirements, the specific energy increases. However, it is evident from Fig. 8 that the increase in rake angle gradually decreases the specific energy.

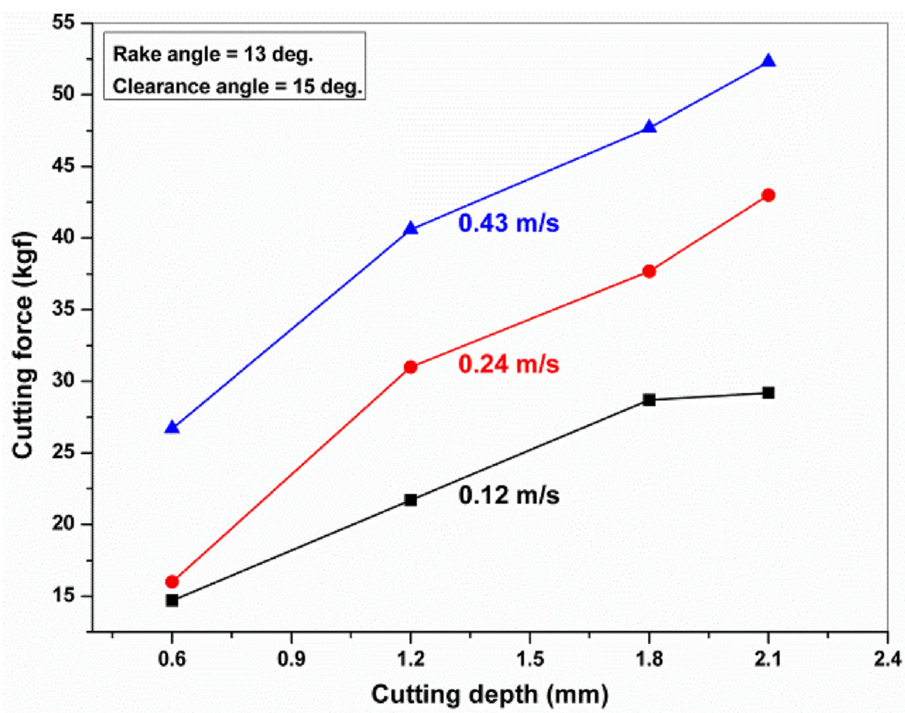

Fig. 4. Determination of cutting forces for different depths and varying speed with a clearance angle of 15°.

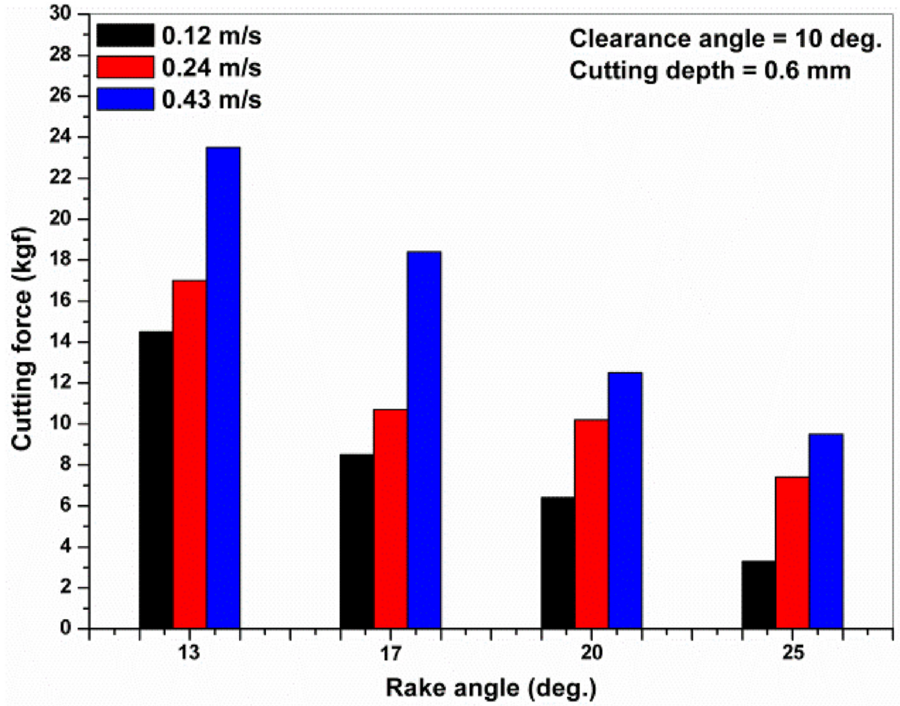

Fig. 5. Variation in cutting forces for different rake angles and varying cutting speed with a depth of 0.6 mm and clearance angle of 10°.

Similar results were observed for increasing cutting depth and machine cutting speed. Decreasing the wedge angle also results in low energy consumption. The specific energy and cutting force have been plotted against a ratio *R* which is determined through equation (2).

$$R = \frac{\text{Cutting depth}}{\text{Cutting speed}} \tag{2}$$

From Figs. 9 and 10 and, 11, the plot of specific energy and force versus the ratio *R* by varying the clearance angle and by keeping the rake angle

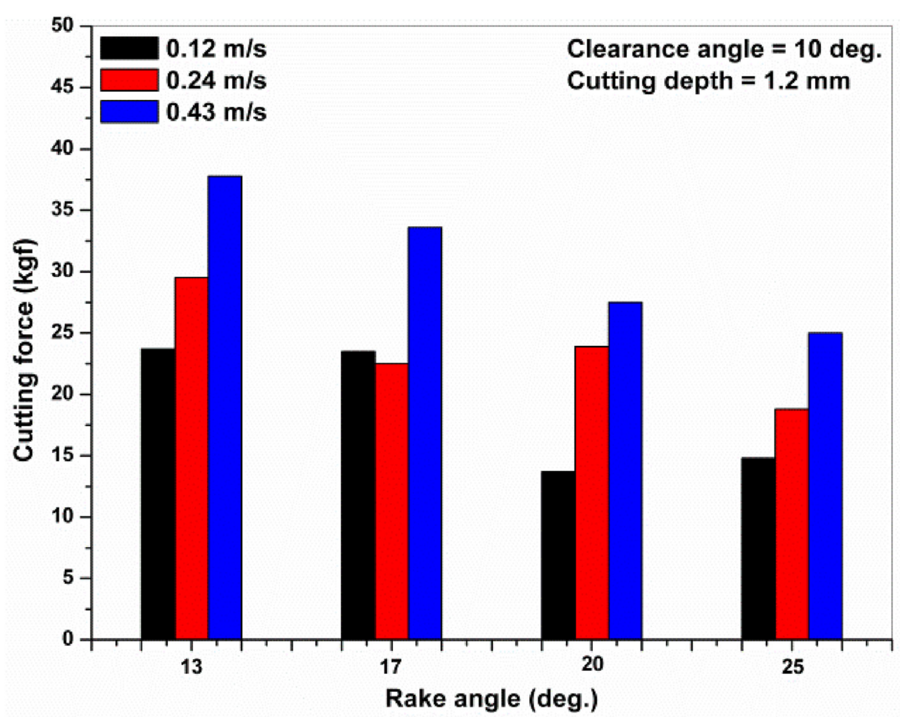

Fig. 6. Variation in cutting forces for different rake angles and varying cutting speed with a depth of 1.2 mm and clearance angle of 10°.

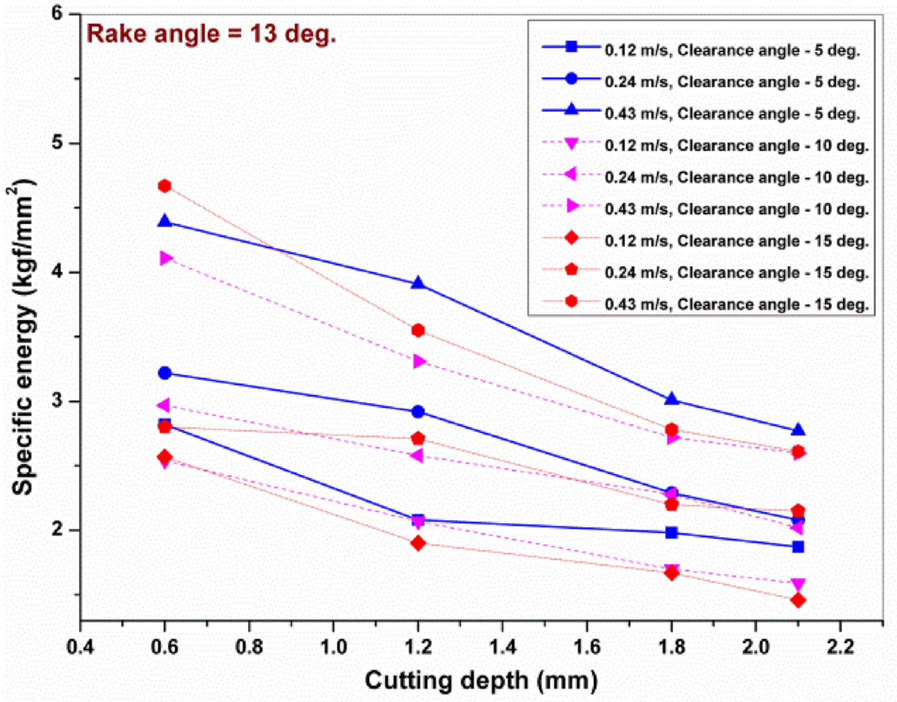

Fig. 7. Specific energy versus cutting depth for different speed and clearance angles with fixed rake angle of 13°.

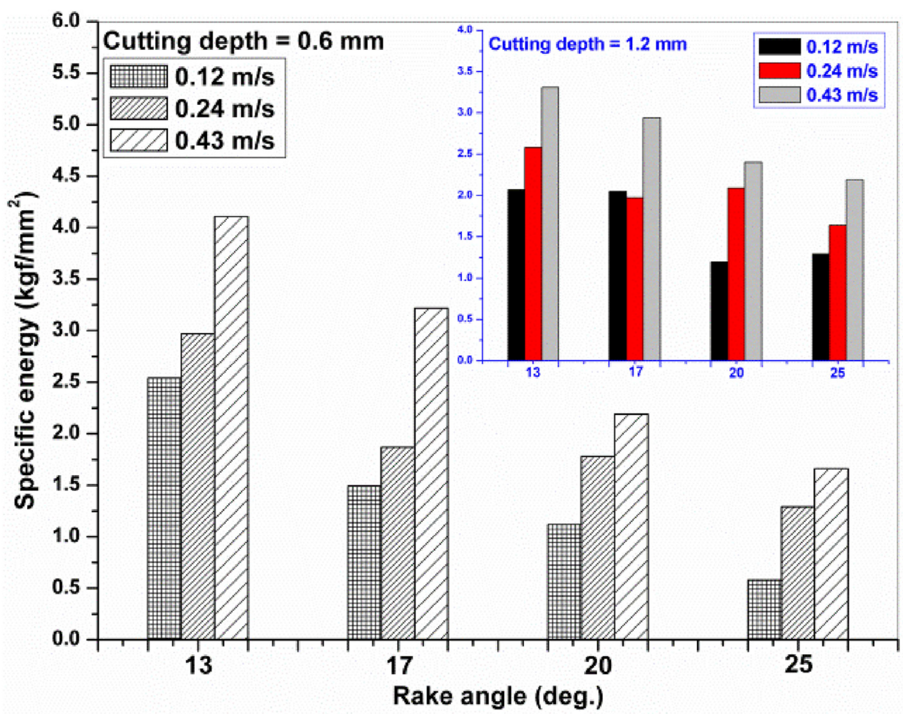

Fig. 8. Specific energy versus different rake angles for varying speed with a fixed cutting depth of 0.6 mm.

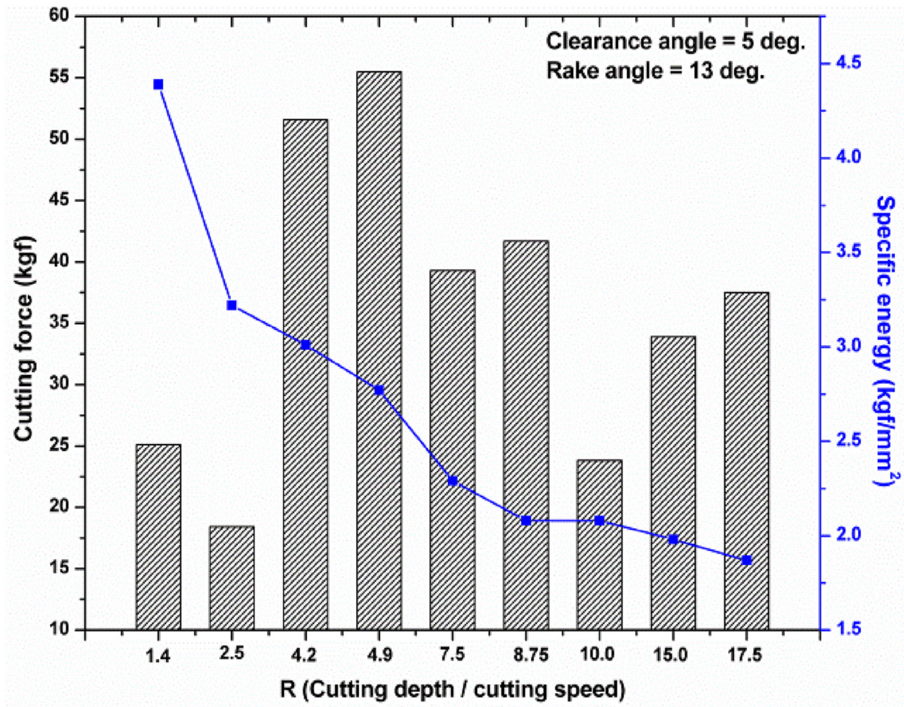

Fig. 9. Cutting forces and specific energy with respect to R for a clearance angle of 5°.

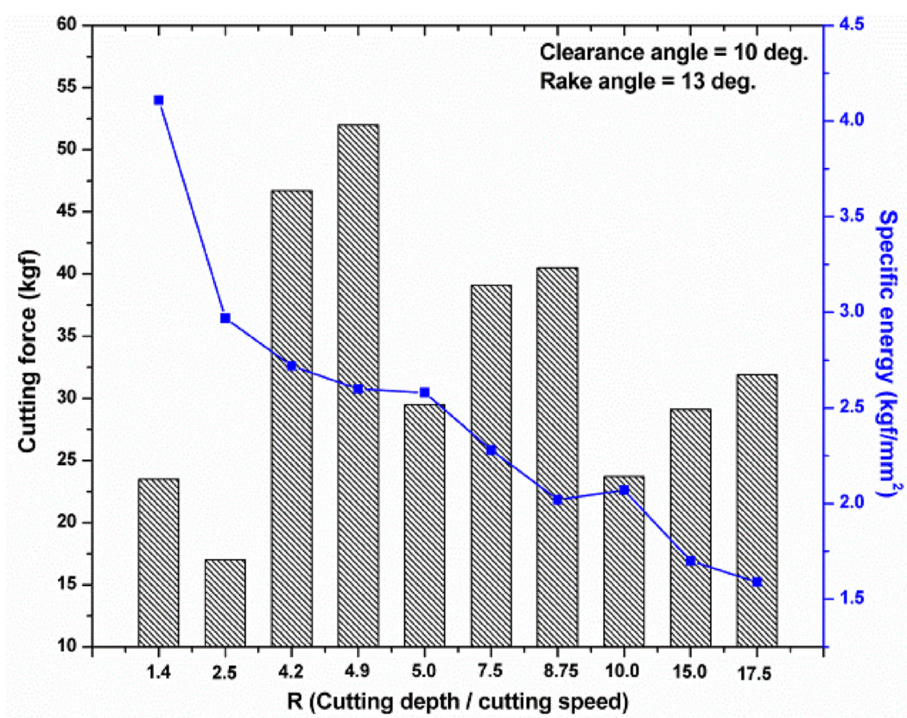

Fig. 10. Cutting forces and specific energy with respect to R for a clearance angle of 10°.

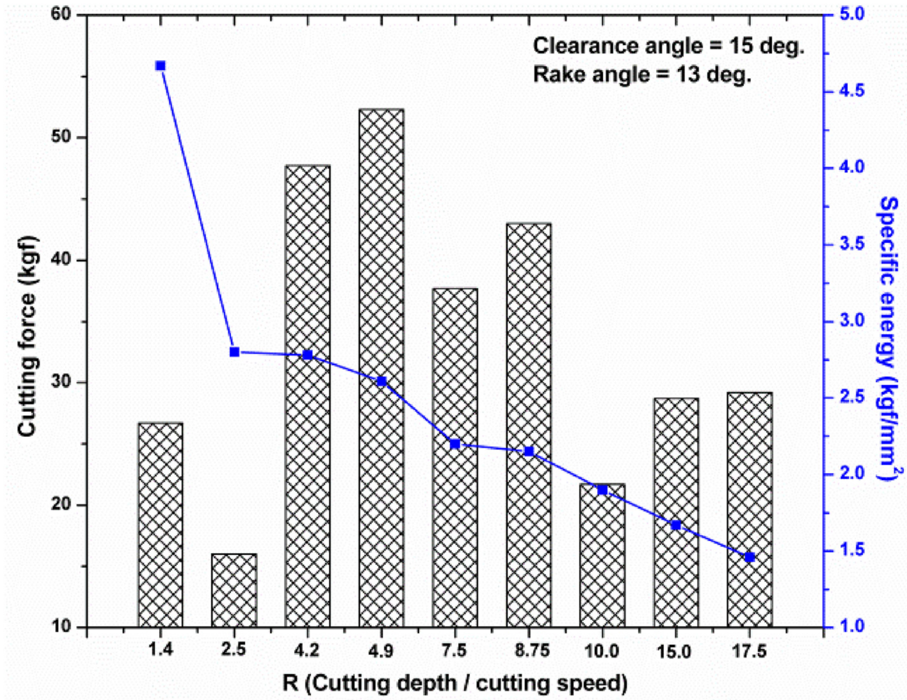

Fig. 11. Cutting forces and specific energy with respect to R for a clearance angle of 15°.

constant gives very interesting results. It can be very easily perceived that the optimum working region is around the point where the force is minimum. This is because, specific energy is also quite low at this point. To work beyond this point is much more advantageous as it gives more lumps (see Fig. 11).

5. Conclusions

It is desirable in a ploughing operation that the energy consumption is low, and the coal is obtained in desired lump size. This has been achieved under certain constraints, like – cutting depth being limited by available machine power, bit strength, and the machine speed, which is also restricted by motor power, etc. To achieve the desired result, it is necessary to optimize various working parameters. The output production rate can be increased by increasing the machine speed, but it creates significant particulate issues. Similarly, the depth can be increased only up to the value at which it does not cause any harm to the motor and the plough picks. The plot of force and specific energy versus the ratio R by varying the clearance angle and keeping the rake angle constant gives way for optimizing various parameters. The operating region should preferably be at the point where the force is minimum, but a large lump size requirement may compel us to operate beyond this value of R. The cutting force elevates at a faster rate with an increase in depth at higher speeds. This also prohibits working at higher speeds. The percentage increase in force is nearly 20% for a speed increase of 20%. The tool wedge angle shall be preferably 50–60°. This is because a clearance angle greater than 5° has no advantage, and for a rake angle of 20–25°, the specific energy curve becomes almost horizontal. Hence, a rake angle greater than this value will only increase the bit consumption rate. Compared to reduced speed, an increase in depth results in a more noticeable increase in lumps percentage. Hence, speed can be decided solely on the basis of face advances rate, whereas depth should be decided based on production as well as the lump size required. The operating region shall be such that $R > 10$. The exact value of R shall depend on the lump size required.

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Conflict of interests

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