

Estimation of rock cutting performance of an actuated undercutting mechanism

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ABSTRACT

Undercutting using an actuated disc cutter (ADC) involves more complex cutting mechanism than traditional rock cutting does, requiring the application of various new cutting parameters, such as eccentricity, cutter inclination angle, and axis rotational speed. This study introduces cutting-edge laboratory-scale testing equipment that allows performing ADC tests. ADC tests were done on a concrete block with a designed strength of 20 MPa under a variety of cutting settings involving penetration depth (p), eccentricity (e), and linear velocity (v). A new approach of calculating the cutting force and specific energy was made. Unlike pick and disc cutting, ADC has a non-linear cutting path with a shifting cutting direction. The cutting path was divided into small segments for examination, and the total work was calculated by adding the segmental multiplication of resultant force and the length of each segment. The specific energy was then determined using the total work performed along the trajectory and the volume of cut rock. The e/p ratio was used to define the optimal specific energy. Based on the limited data available in this investigation, it was determined that the optimal cutting conditions are obtained at an e/p ratio of 1.86 for p of 3 mm and v between 20 and 40 mm/s. In general, actuated undercutting provides a more efficient cutting than traditional pick and disc cutting by showing fairly lower specific energy in a relatively similar cutting environment.

1. INTRODUCTION

Mechanical cutting studies have focused on two types of cutting: roller disc cutting and drag pick cutting. Both mechanisms have their pros and cons. Roller disc cutting

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needs a high thrust force to induce tensile failure, but the mechanism allows the contact zone between rock and tool to change during the process, reducing thermal stress-induced wear (Hood and Alehossein 2000). On the other hand, drag pick cutting requires less energy than disc cutting because the tensile failures are generated more directly. However, the dragging mechanism is prone to wear due to constant contact of the same area of the tool throughout the procedure (Hood and Roxborough 1992).

Rock cutting using an undercutting disc cutter (UDC) has been proposed as an alternative method that benefits both rolling and dragging mechanisms. The undercutting concept allows a rolling disc to be dragged across the rock surface like a pick cutter. Because tensile fractures are formed directly, and thermal wear is dispersed evenly due to the rotational movement of the disc, the combination of these two principles results in an efficient cutting. Hood and Alehossein (2000) emphasized the significance of this principle, which permits a hard rock to be excavated efficiently without causing excessive wear of a cutter. The principle is implemented in certain types of mining machinery, such as Wirth's Continuous Mining Machine and Tunnel Boring Extender (Ramezanzadeh and Hood 2010).

Recently, the UDC technique has been advanced to undercutting with oscillated disc cutter (ODC) and actuated disc cutter (ADC), in which the disc can oscillate at small amplitudes with the aid of an internal motor. ADC adopts the characteristics of an ODC with the addition of a free rotational mechanism in a second axis that is not concentric with the main motored-rotational axis. The ADC mechanism enables easy adjustment of the oscillation amplitude and frequency of the rotation via its secondary axis (Dehkhoda and Detournay 2017, 2019; Dehkhoda and Hill 2019).

This paper analyzed some results based on the undercutting test using ADC performed by a state-of-the-art undercutting test rig. We performed tests with various parameters such as penetration depth, actuation amplitude (eccentricity), and linear velocity. Additionally, we developed a new method for calculating the specific energy, which differs from the technique used in the traditional disc and pick cutting.

2. CUTTING TEST USING ADC METHOD

2.1. ADC Mechanism

A thorough assessment of the mechanics of actuated undercutting has been introduced in Dehkhoda and Detournay (2017, 2019) and Jeong et al. (2020b). The mechanism of the actuated undercutting system is unique in that it involves two axes. The main axis is where the system rotates, whereas the secondary axis is the center of the disc, which can be modified off-centric to the main axis. Eccentricity (e) is defined as the distance between the disc center and the point of system rotation. The system revolves at a constant angular velocity (ω) around the primary axis. The undercutting disc is attached to a cartridge and moves with a constant linear velocity (v) parallel to the cutting direction. The movement of a disc is determined by the product of translation and actuation relative to the main axis. The disc rotates freely around its axis, cutting the rock surface at a constant depth (p). The operation will produce a cut volume with a consistent depth and width. The parameters e , ω , v , p , and the radius of the undercutting disc (d) define the trajectory of the undercutting disc, as well as the geometry of the cut rock surface. Additionally, the disc can be tilted (tilt angle α) throughout the cutting process to

avoid excessive friction on the flat surface of the disc. The schematic mechanism can be seen in Fig. 1.

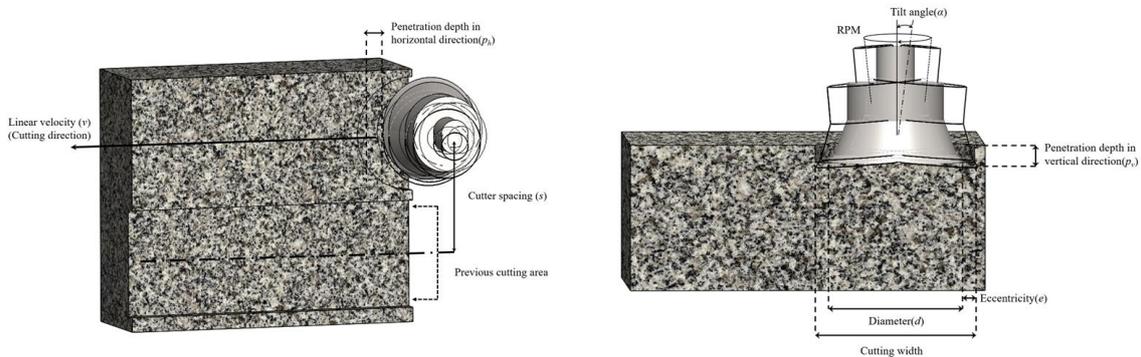


Fig. 1. Cutting parameters for an undercutting using actuated disc cutter (Jeong et al. 2021)

2.2. ADC Testing System

The actuated undercutting test system built by Seoul National University is shown in Fig. 2a. The machine consists of a rigid platform, electric motors, a three-dimensional load cell, a mounting system for the actuated disc, a rock block container, and a data acquisition system connected to a personal computer. The load cell is capable of recording forces in three orthogonal axes and has a capacity of 20 tons. The system is equipped with three electric motors. The vertical motor is used to control the penetration depth, while the horizontal motor is used to drive the linear movement at a maximum speed of 100 mm/s. Another electric motor with a maximum RPM of 800 and a torque of 1000 Nm serves as the system's rotational motor. Except for eccentricity and tilt angle, which must be adjusted manually, other parameters can be modified via built-in controller and software.

Fig. 2b shows a typical rock block after the ADC test. The sample container can hold a rock block up to 300 mm x 300 mm x 300 mm in size. Given the maximum specimen size, installing the full-size disc from the real excavation equipment, which is typically 500 to 550 mm in diameter, is incompatible. Therefore, the scaled-down disk cutter should be utilized, and the effect on the scale should be taken into account. Scaled-down ADC is available in various sizes in the laboratory, ranging from 60 to 150 mm in diameter (see Fig. 2c). As shown in Table 1, the scaling ratio is calculated through dimensional analysis. For instance, we used a 60 mm ϕ ADC in the laboratory to cut a concrete block of 20 MPa in uniaxial compressive strength and a density of 2.1 gr/cm³. In actual operation, we presume to use a 500 mm ϕ ADC to cut a rock with a density of 2.6 gr/cm³. Assuming that the gravitational acceleration is constant, the ratio of the rest of the dimensional variables can be derived. Based on the dimensional analysis, it can be inferred that the strength of the material tested in the laboratory is reduced 10.3 times from the actual condition ($1/0.097 = 10.3$). In other words, the 20 MPa specimen in the laboratory experiment is equivalent to about 206 MPa in the actual cutting operation.

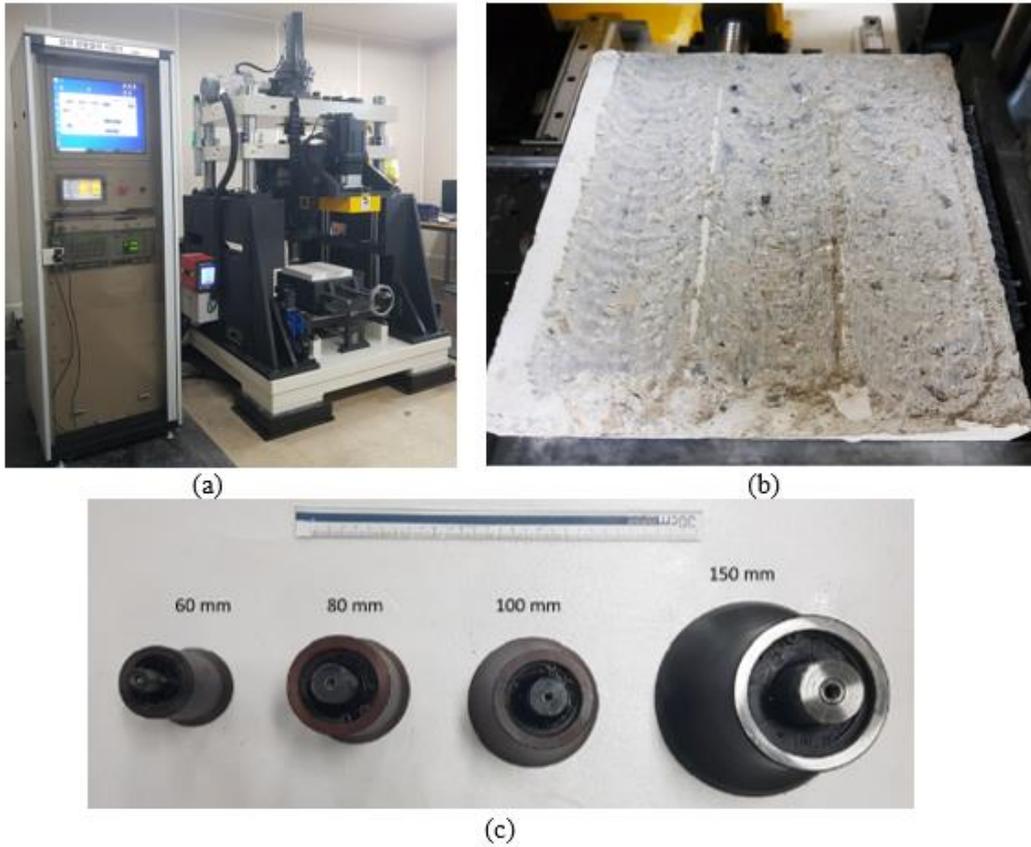


Fig. 2. Actuated undercutting testing system. (a) the machine, (b) typical of specimen after test, (c) scaled-down ADC in various sizes

Table 1. Scaled condition used in the experiment (ADC diameter = 60 mm, specimen density = 2.1 gr/cm³)

Variable	Dimension	Measure		Ratio
		Scaled	Actual	
Length	L	60	500	0.120
Gravity	LT ⁻²	9.81	9.81	1.000
Density	ML ⁻³	2.1	2.6	0.808
Time	T	-	-	0.346
Mass	M	-	-	0.001
Strength and stress	ML ⁻¹ T ⁻²	-	-	0.097

3. SPECIFIC ENERGY CALCULATION

The concept of specific energy is introduced to evaluate the rock cutting performance. The term specific energy refers to the work performed by a cutter to cut a unit volume of rock, as shown in Eq. (1).

$$SE = \frac{\text{Work done}}{\text{Volume}} \quad (1)$$

In standard disc and pick cutting, the cutting direction is linear, and the force can be represented by force dominant parallel to the cutting direction. Thus, the work performed by the cutter on a typical traditional cutting can be calculated using Eq. (2).

$$W = \vec{F}_c \cdot \vec{l} = |\vec{F}_c| |\vec{l}| \cos\theta \quad (2)$$

where F_c is the cutting force, l is the cutting length, and θ is the angle between the force direction and the cutting direction.

However, in actuated undercutting, the cutting force and side force play a significant role in the cutting operation. As a result, work is derived in a slightly more complex form by including side force. The DAQ system of the machine is capable of recording three-dimensional force at the rate of 1000 Hz. The quick data interval enables segmentation of the cutting trajectory into smaller linear segments every one millisecond. As a result, the work is denoted by Eq. (3).

$$W = \sum (|\vec{F}_c + \vec{F}_s| \cdot dl \cdot \cos\theta) \quad (3)$$

where F_c is the cutting force, F_s is the side force, and dl is the cutting length in a small interval.

The cut volume is simplified and assumed to be cuboid in shape because the excavation produces a flat surface with straight side boundaries. Thus, as illustrated in Eq. (4), the cutting volume is theoretically estimated.

$$V_{cut} = (d + 2e)pl \quad (4)$$

where d is the diameter of the cutter, e is the eccentricity, p is the penetration depth, and l is the cutting length.

So, considering the work and volume calculations explained above, the specific energy can be denoted as Eq. (5). The schematic description of the calculation is depicted in Fig. 3.

$$SE = \frac{1}{V_{cut}} \sum (|\vec{F}_c + \vec{F}_s| \cdot dl \cdot \cos\theta) \quad (5)$$

4. EXPERIMENT RESULT

This study used the ADC of 60 mm diameter, constant penetration depth (p) of 3 mm, and constant RPM of 70. A total of nine cases were performed with various linear velocities (v) of 20 mm/s, 30 mm/s, and 40 mm/s, and eccentricity (e) of 3.75 mm, 5.60 mm, and 7.50 mm. Cutter force in three orthogonal directions, namely cutting, side, and normal forces, were recorded throughout each test. The specific energy for each case

was calculated based on Eq. (5). Representative cutter forces at a single case are depicted in Fig. 4; the experiment results are summarized in Table 2.

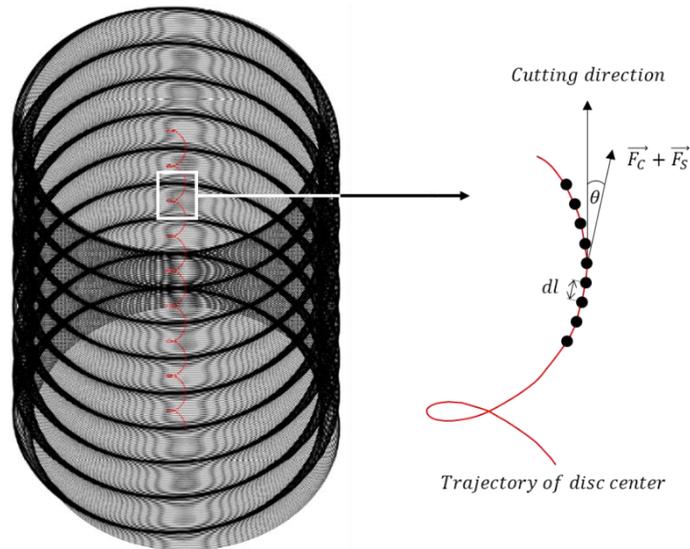


Fig. 3. Sample of cutting trajectory of ADC and specific energy calculation

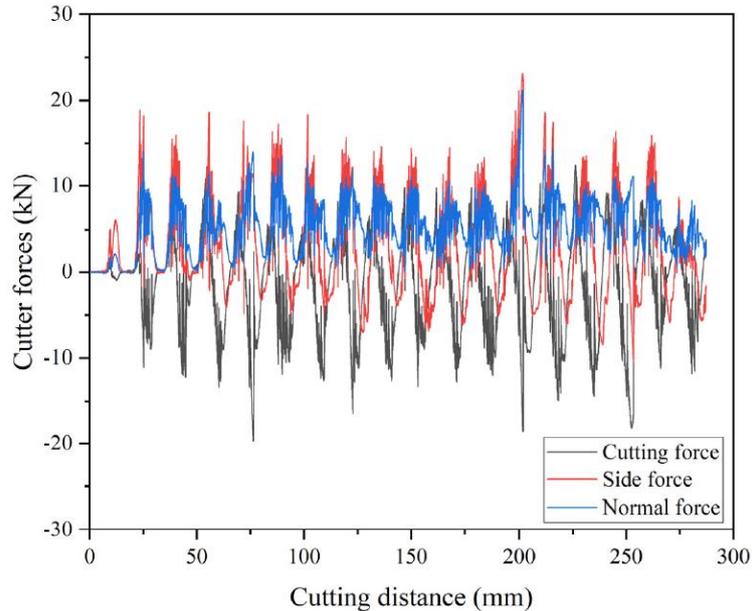


Fig. 4. Representative cutter forces of ADC at the case of $d = 60$ mm, $v = 20$ mm/s, $p = 3$ mm, $e = 7.5$ mm, RPM = 70

Table 2. Results of ADC test

Case	v (mm/s)	e (mm)	e/p	Mean cutter force (kN)			SE (MJ/m ³)
				Cutting	Side	Normal	
1	20	3.75	1.25	7.83	4.09	6.41	35.03
2	20	5.60	1.86	6.76	4.36	5.87	23.06
3	20	7.50	2.50	6.05	4.63	5.43	33.69
4	30	3.75	1.25	9.97	5.96	9.97	59.33
5	30	5.60	1.86	9.61	7.21	10.06	40.56
6	30	7.50	2.50	6.59	4.63	5.96	43.85
7	40	3.75	1.25	6.59	6.41	8.01	44.17
8	40	5.60	1.86	6.76	6.23	7.92	41.96
9	40	7.50	2.50	8.63	5.16	7.83	43.85

5. DISCUSSION

In traditional disc and pick cutting, the optimum cutting is usually expressed as a function of the s/p ratio, the ratio of line spacing between two cutters and penetration depth.

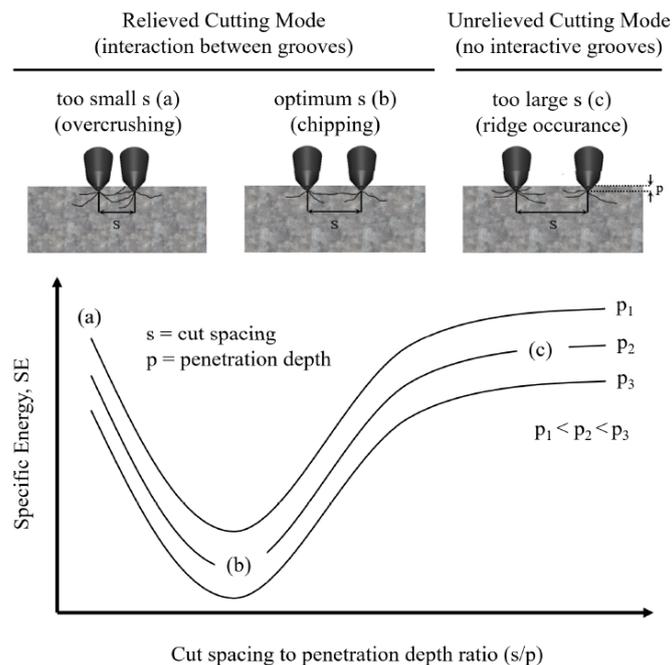


Fig. 5. The influence of line spacing and penetration depth on specific energy and cutting efficiency (modified from Bilgin et al. 2014)

Fig. 5 illustrates the influence of line spacing and penetration depth on specific energy and cutting efficiency (Bilgin et al, 2014). If the line spacing is too small (case a), the specific energy becomes extremely high, and the cutting becomes inefficient due to

the over-crushing of the rock. If the line spacing is too large (case c), the specific energy is also high, and the process is inefficient because the tensile cracks from neighboring cuts cannot connect to form a chip (unrelieved cut). The lowest specific energy is attained by optimizing the s/p ratio, as illustrated in case b, which results in the most efficient cutting condition and produces the largest rock chips.

Undercutting with ADC, on the other hand, does not rely on neighboring cuts to produce chips. ADC enables the generation of tensile cracks in a direct manner, and the tensile cracks propagate directly towards the free surface. In this circumstance, the s/p ratio is irrelevant in determining the optimal cutting condition. Rather than that, we attempt to use the e/p ratio, which is the eccentricity to penetration depth ratio. Eccentricity is defined as the offset between the disc axis and the main rotational axis. Thus, the unit length of eccentricity contributes to the amount of rock excavated while also affecting the force being used to cut the rock. Therefore, the cutting efficiency will be specified by the minimum SE value under various e/p ratio settings.

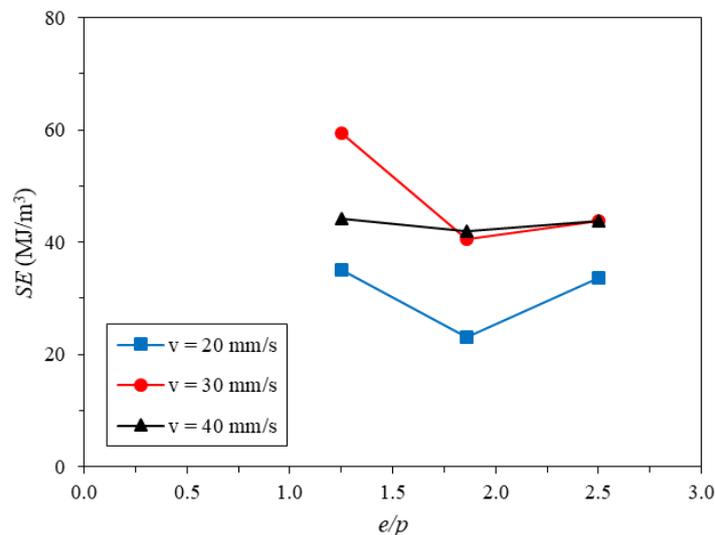


Fig. 6. Results of specific energy in various linear velocity and e/p ratio scenarios

Fig. 6 illustrates the influence of the e/p ratio and linear velocity on specific energy. The graph demonstrates that specific energy varies with the e/p ratio, with the lowest SE at $e/p = 1.86$. The results in this current study, however, are somewhat optimistic because the sampling data are limited. Nevertheless, the result indicates that using the e/p ratio as a parameter to define optimum cutting conditions could work. Additionally, Fig. 6 demonstrates that SE tends to decrease with decreasing cutting velocity, although this is obvious only for the case of 20 mm/s. Based on these findings, it is anticipated that cutting efficiency should be examined using the combination of e/p ratio and linear cutting velocity and potentially other cutting parameters such as rotational speed and tilting angle.

Another important issue is how the ADC performs compared to traditional disc and pick cutting. Table 3 summarizes the optimum ADC cutting condition from the current investigation compared to conventional disc and pick cutting. Based on work done by

Cho et al. (2003), at the optimum condition, disc cutting yielded SE values in the range of 35-42 MJ/m³ from the laboratory cutting test and 37-43 MJ/m³ from numerical simulation. In the case of pick cutting, Jeong et al. (2020a) reported SE values ranging from 37 to 68 MJ/m³ in laboratory testing and 41 to 43 MJ/m³ in numerical modeling. The optimal condition in the current study ranges from 23 MJ/m³ to 42 MJ/m³. Despite the fact that it is difficult to say if ADC performs better or not at the present study due to a lack of data, it is a solid indication, in which the SE value might drop as low as 23 MJ/m³ with ADC. Future work using a more extensive database is necessary to confirm the current findings.

Table 3. Cutting efficiency of ADC compared to traditional disc and pick cutting

Optimum cutting configuration		SE (MJ/m ³)		Cutting mechanism	Reference
p (mm)	s/p or e/p	Laboratory	Numerical		
4	s/p = 10	41.70	43.10	Disc cutting	Cho et al. (2013)
6	s/p = 10	37.60	40.50		
8	s/p = 7.5	35.00	37.80		
5	s/p = 4	67.57	41.05	Pick cutting	Jeong et al. (2020a)
7	s/p = 3	42.17	40.99		
9	s/p = 3	33.12	42.08		
11	s/p = 3	31.10	43.10		
3	e/p = 1.86 (v = 20 mm/s)	23.06	-	Undercutting with actuated disc cutter	Present study
3	e/p = 1.86 (v = 30 mm/s)	40.56	-		
3	e/p = 1.86 (v = 40 mm/s)	41.96	-		

6. CONCLUSION

This study introduces the testing method that enables evaluating cutting performance based on the undercutting method using an actuated disc cutter (ADC). Due to the fact that ADC has a different cutting mechanism than disc or pick cutting, the testing parameters and performance evaluation are also different. Unlike the conventional method, ADC operates on non-linear trajectories in which the cutting direction changes throughout the test. As a result, a new approach for calculating cutting force and specific energy is introduced that considers the resultant force and its orientation relative to the cutting direction. The commonly used s/p ratio cannot be used to determine the cutting efficiency of ADC. Instead of that, the e/p ratio concept is proposed and tested using a simple laboratory test case. The efficient cutting condition can be portrayed from the result, but a more extensive database is needed to confirm the current finding. According to this study, ADC performs better than traditional cutting by exhibiting lower specific energy at its optimum cutting condition, although further research is required to provide more evidence.

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