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Cutter cutting cobalt-rich crusts with water jet

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1. Introduction

As land mineral resources are exhausting, many countries are paying attention to deep sea resources development and utilization. Deep sea cobalt-rich crusts are metal mineral, which is locates in sea mountain [1, 2]. Deep sea cobalt-rich crusts are rich in rare metals Co and Pt. It is widely considered as one of the most attractive ocean floor mineral resources. Considering economic value and strategic significance of deep sea cobalt-rich crusts resources, exploitation techniques of deep sea cobalt-rich crusts resources are studied widely [3, 4]. One of research directions is about cobalt-rich crusts resources cutting method. Spiral drum cut teeth cutting is seen as an effective cobalt-rich crusts cutting method. In order to improve cutting efficiency, cobalt-rich crusts vibration cutting method is proposed. In this method, an eccentric mechanism is amounted in spiral drum. When spiral drum rotating, an additional vibration cutting force is generated and cutting efficiency of cobalt-rich crusts is increased.

In a real deep sea cobalt-rich crusts mining system, high cutting efficiency is important, but safety of mining system is more important. Impact load and vibration of spiral drum are inevitable when cutter cutting deep sea cobalt-rich crusts. Excessive impact load may lead mining vehicle dumping is proposed in reference [5]. Method of cutter cutting cobalt-rich crusts with water jet is proposed in this paper to improve the safety of mining system and to decrease impact load of cutter. In this method, high pressure water jet is used to assist cutter cutting cobalt-rich crusts. With water jet helping, cutting force and impact load of cutter are decreased [6, 7].

In order to obtain the working mechanism of water jet assists cutter cutting cobalt-rich crusts and the action law of water jet parameters and its cutting performance, the process of cutter cutting cobalt-rich crusts with water jet was studied with simulation calculation and experiment test[8, 9].

2. Modeling

The operating principle of cutter cutting cobalt-rich crusts with water jet is as follows: cutting force of cutter *F* and water jet pressure *P* are applied to the surface of the cobalt crusts at the same time. Initial crack is generated when the resultant force of cutter and water jet is great than cobalt-rich crusts compressive strength. Water jet enters into aperture and extrusion stress and tensile stress are generated after initial crack is formed. Extrusion strength and tensile strength of cobalt-rich crusts are less than compressive strength. So the needed minimum cutting force of cutter is decreased with water jet auxiliary cutting. The schematic of cutter cutting cobalt-rich crusts with water jet is shown in Fig. 1, *F* is cutter cutting force, *P* is water jet pressure, *w* is the distance between action point of cutting force *F* and action point of water jet.

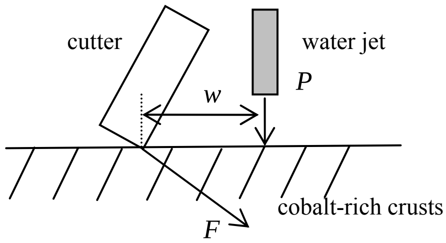

Fig. 1 Schematic of cutter cutting cobalt-rich crusts with water jet

When cutter cutting cobalt-rich crusts, the condition of forming initial crack on cobalt-rich crusts surface is stress of cutter at action point σ_{yk} is great than cobalt-rich crusts critical compressive strength σ_{yo}, that is

$$\sigma_{yk} > \sigma_{y0} \tag{1}$$

In Eq. (1), σ_{yk} is stress of cutter at action point.

When cutter cutting cobalt-rich crusts with water jet, the condition of forming initial crack on cobalt-rich crusts surface is resultant stress of cutter and water jet at a point is great than cobalt-rich crusts critical compressive strength σ_{y0}, that is

$$\sigma_{y2k} + \sigma_w \geq \sigma_0 \tag{2}$$

In Eq. (2), σ_w is stress of water jet at point of initial crack, σ_{y2k} is stress of cutter at point of initial crack.

From Eq. (1) to Eq. (2), it shows that with water jet auxiliary cutting, the needed stress of cutter to form initial crack can reduce σ_w in ideal conditions. The stress on cobalt-rich crusts surface generated by water jet is mainly concentrated in jet around the point. So the distance between water jet action point and cutter action point is a key parameter of cutter cutting cobalt-rich crusts with water jet. In order to obtain the action law, simulation researches on distance between water jet action point and cutter action point with water jet working performance were carried out.

Fig. 2 is finite element model of cutter cutting cobalt-rich crusts with water jet. During simulation, concentrated force load *F* is applied to point *e*, pressure load *P* is applied to *f*, boundary of *ab*、*bc* and *cd* are set as fixed boundary. Parameters of cobalt-rich crusts are as follows, elastic modulus is 3500 MPa, compressive strength is 8 MPa, tensile strength is 0.5 MPa, Poisson Ratio is 0.25, width of water jet action point is 2 mm, water jet pressure *P* is 3 ~ 8 MPa. Cutting force *F* of cutter is 450 ~ 900 N, width of cobalt-rich crust is 30 mm, height is 20 mm. distances between cutter action point and water jet action point is 0 ~ 4 mm.

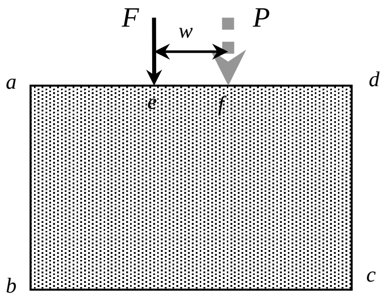

Fig. 2 Finite element model of cutter cutting with water jet

3. **Simulation results**

In order to carry out comparative study, conditions of forming initial crack on cobalt-rich crusts surface were simulated at first, which was generated by cutter or water jet. Maximum equivalent stress (MES) of cobalt-rich crusts with different cutter cutting force is shown in Table 1, which shows with the increasing of cutter cutting force, MES of cobalt-rich crusts is increased corresponding. When cutting force $F < 970$N, MES generated by cutter is less than cobalt-rich crusts compressive strength 8 MPa, which shows cutter can't generate initial crack on cobalt-rich crusts surface. When cutting force $F > 970$N, MES generated by cutter is great than cobalt-rich crusts compressive strength 8 MPa, which shows cutter can generate initial crack on cobalt-rich crusts surface. So when cutter cutting cobalt-rich crusts, the condition of forming initial crack on cobalt-rich crusts surface is minimum cutting force of cutter is no less than 970 N.

Table 1

MES with different cutting force *F*

Cutting force, N	600	700	800	900	970	1000
MES, MPa	4.9	5.8	6.6	7.4	8	8.3

MES of cobalt-rich crusts with different water jet pressure is shown in Table 2, which shows with the increasing of water jet pressure, maximum equivalent stress is increased corresponding. When water jet pressure $P < 7.8$MPa, MES generated by water jet is less than cobalt-rich crusts compressive strength 8 MPa, which shows water jet can't generate initial crack on cobalt-rich crusts surface. When water jet pressure $P > 7.8$MPa, MES generated by water jet is great than cobalt-rich crusts compressive strength 8 MPa, which shows water jet can generate initial crack on cobalt-rich crusts surface. So when water jet cutting cobalt-rich crusts, the condition of forming initial crack on cobalt-rich crusts surface is minimum water jet pressure is no less than 7.8 MPa.

Table 2

MES with different water jet pressure *P*

Water jet pressure, MPa	4	5	6	7	7.8	8
MES, MPa	4.2	5.3	6.3	7.3	8	8.4

Fig. 3 is equivalent stress distribution of cobalt-rich crusts generated by cutter and water jet while $F = 970$ N, $P = 5$ MPa, $w = 4$ mm. Two stress concentrated area are formed around cutter action point and water jet action point, which shows cutter cutting force and water jet pressure are act on cobalt-rich crusts surface at the same time. Maximum equivalent stress is located on cutter action point, which shows MES generated by cutter is great than water jet in the current conditions. MES on cutter action point is 7.95 MPa and it is less than MES generated by cutter alone, which shows using of water jet can't decrease the needed minimum cutting force of cutter in the current conditions.

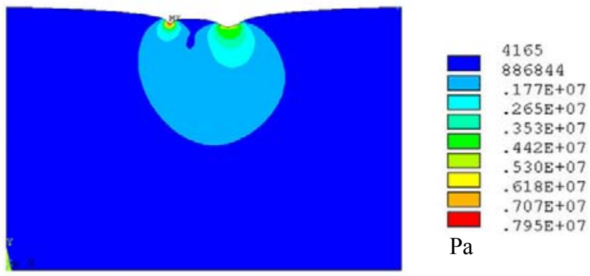

Fig. 3 Equivalent stress distribution of cobalt-rich crusts ($F = 970$ N, $P = 5$ MPa, $w = 4$ mm)

MES of cobalt-rich crusts with different distance w are shown in Table 3. When water jet action point isn't overlap with cutter action point, MES of cobalt-rich crusts is decreased compared with cutter cutting alone, which shows using of water jet can decrease cutter cutting performance in the current conditions. When water jet action point is overlap with cutter action point, MES of cobalt-rich crusts is increased compared with cutter cutting alone, which shows using of water jet can increase cutter cutting performance obviously in the current conditions.

Table 3

MES with different *w* ($F = 970$ N, $P = 5$ MPa)

w, mm	0	1	2	3	4
MES, MPa	13.3	7.95	7.95	7.95	7.95

MES of cobalt-rich crusts with different water jet pressure (w = 4 mm, F = 970 N) are shown in Table 4. When water jet pressure is less than 8 MPa, with the increasing of water jet pressure, MES of cobalt-rich crusts is decreased, which shows water jet hinder cutter cutting cobalt-rich crusts in the current conditions. When water jet pressure is great than 8 MPa, MES of cobalt-rich crusts is great than compressive strength of cobalt-rich crusts, which shows initial crack has formed. So the condition of water jet assists cutter cutting cobalt-rich crusts is water jet action point is overlap with cutter action point.

Table 4

MES with different P(w = 4 mm, F = 970 N)

P, MPa	4	5	6	7	8
MES, MPa	7.96	7.94	7.93	7.91	8.34

Fig. 4 is equivalent stress distribution of cobalt-rich crusts generated by cutter and water jet when F = 350 N, P = 5 MPa, w = 0 mm. It shows MES is locates at cutter action point, which shows water jet action point is overlap with cutter action point. MES of cobalt-rich crusts is 8.1 MPa and it is great than cobalt-rich crusts compressive strength 8 MPa, which shows initial crack has formed on cobalt-rich crusts surface. Compared with cutter cutting cobalt-rich crusts alone, the needed cutting force of cutter decreased by 55%, which shows using of water jet can decrease needed cutting force of cutter obviously.

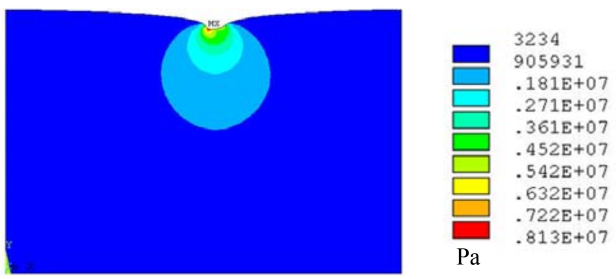

Fig. 4 Equivalent stress distribution of cobalt-rich crusts (F = 350 N, P = 5 MPa, w = 0 mm)

The needed minimum cutter cutting force to generate initial crack on cobalt-rich crusts surface with different water jet pressure while w =0 mm are shown in Table 5, which shows with the increasing of water jet pressure, the needed minimum cutting force is decreased obviously. So water jet assists cutter cutting cobalt-rich crusts can improve cutting efficiency obviously.

Table 5

Needed cutter cutting force with different P (w = 0 mm)

P, MPa	2	3	4	5	6	7	8
Cutting force, N	730	600	475	350	220	100	0

4. Experimental tests

Experiment test of cutter cutting cobalt-rich crusts simulation materials with water jet were carried out to validate simulation conclusions. It is difficult to obtain deep sea cobalt-rich crusts. So, cobalt-rich crusts simulation materials were used in experiment test. Development method of deep sea cobalt-rich crusts simulation materials is accord to reference [10]. Simulation materials adopted sand, lime and gypsum made by certain proportion. Main parameters of simulation materials are as follows, compressive strength is 6~8 MPa, shear strength is 0.4~0.6 MPa

It is difficult to measure cutter cutting force from experimental device directly. Acceleration sensors were placed on support of cutter. During the process of cutter cutting cobalt-rich crusts simulation materials, vibration signals of cutter were measured to analyze variation of cutting force. Normal acceleration curve of cutter cutting cobalt-rich crusts simulation materials is shown in Fig 5, which shows that obvious impact load is existed during cutter cutting cobalt-rich crusts simulation materials. Maximum acceleration is about 300 m/s^2 and root mean square of acceleration is about 50 m/s^2. When water jet pressure is 5 MPa and distance between water jet action point and cutter action point is 3 mm, normal acceleration of cutter was shown in Fig. 5. Measurement results show when water jet action point is not overlap with cutter action point, acceleration curve of cutter with water jet is almost to cutter cutting alone, maximum acceleration is about 300 m/s^2, root mean square is decreased and the value is about 45 m/s^2.

When water jet pressure is 5 MPa and water jet action point is overlap with cutter action point, normal acceleration of cutter was shown in Fig. 6, which shows that obvious impact load is existed during cutter cutting cobalt-rich crusts simulation materials with water jet. Maximum acceleration is about 200 m/s^2 and root mean square of acceleration is about 40 m/s^2.

The following conclusions can be obtained from experimental results. When water jet pressure is less than simulation materials compressive strength and water jet action point is not overlap with cutter action point, maximum impact load of cutter during cutting simulation materials is almost the same compared with cutter cutting simulation materials alone, root mean square of impact load is decreased by 10%. When water jet action point is overlap with cutter action point, maximum impact load of cutter during cutting simulation materials is decreased obviously and approximately 50% decline, root mean square of impact load is also decreased by 10%.

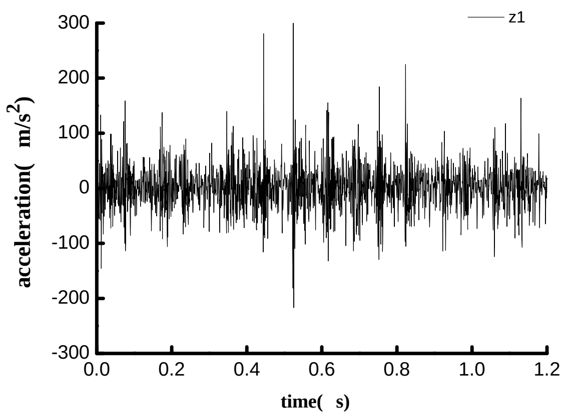

Fig. 5 Acceleration curve of cutter cutting

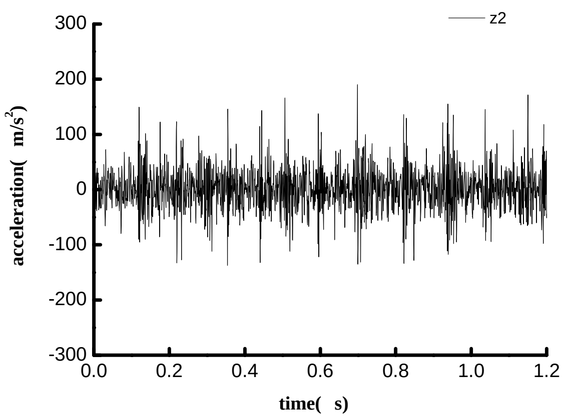

Fig. 6 Acceleration curve of cutter with water jet

5. Conclusions

As impact load is exists in the process of cutter cutting cobalt-rich crusts. Method of cutter cutting cobalt-rich crusts with water jet is proposed to decrease impact load of cutter, which can improve the safety of mining system. With simulation research and experimental tests, the working mechanism of cutter cutting cobalt-rich crusts is obtained. The results obtained are as follows.

1. Simulation results of cutter cutting cobalt-rich crust with water jet show that the distance between water jet action point and cutter action point is key parameter to decrease needed minimum cutting force of cutter, which is used to generate initial crack on cobalt-rich crusts surface. When water jet action point is not overlap with cutter action point, using of water jet can' t decrease the needed minimum cutting force of cutter. When water jet action point is overlap with cutter action point, using of water jet can decrease the needed minimum cutting force of cutter obviously.

2. Experimental results of cutter cutting cobalt-rich crust simulation materials with water jet show that the distance between water jet action point and cutter action point is key parameter to decrease maximum impact load of cutter. When water jet action point is not overlap with cutter action point, using of water jet can't decrease maximum impact load of cutter, but the root mean square of impact load is decreased. When water jet action point is overlap with cutter action point, using of water jet can decrease maximum impact load of cutter obviously and the root mean square of impact load is also decreased.

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PJOVIKLIS KOBALTO PRISOTINTAM PAVIRŠIUI PJAUTI VANDENS SROVE

R e z i u m ė

Kobalto prisotinto paviršiaus pjovimo metodas taikomas vandens srovės pjoviklio smūginei apkrovai sumažinti. Buvo sukurtas pjoviklio kobalto prisotintam paviršiui pjauti vandens srove baigtinių elementų modelis ir buvo imituojamos pradinio plyšio formavimo kobalto prisotintame paviršiuje sąlygos. Imitavimo rezultatai parodė, kad, kai vandens srovės slėgis yra mažesnis už kobalto prisotinto paviršiaus gniuždymo stiprumo ribą ir vandens srovės veikimo taškas iš dalies nesutampa su pjoviklio veikimo tašku, vandens srovė negali sumažinti minimalios pjoviklio pjovimo jėgos, kuri yra naudojama pradiniam plyšiui sudaryti. Kai vandens srovės veikimo taškas sutampa su pjoviklio veikimo tašku, vandens srovė gali efektyviai sumažinti minimalią pjovimo jėgą. Jei vandens srovės slėgis yra didesnis už kobalto prisotinto paviršiaus gniuždymo stiprumo ribą, tik vandens srovė gali sudaryti pradinį plyšį kobalto prisotintame paviršiuje. Buvo atlikti bandymai, imituojantys kobalto prisotinto paviršiaus pjovimą pjovikliu su vandens srove. Šie bandymai parodė, kad, kai vandens srovės veikimo taškas nesutampa su pjoviklio veikimo tašku, vandens srovė negali sumažinti maksimalios pjoviklio smūgio jėgos, bet gali sumažinti smūgio jėgos vidutinį kvadratinį nuokrypį. Kai vandens srovės veikimo taškas sutampa su pjoviklio veikimo tašku, vandens srovė gali gerokai sumažinti maksimalią smūgio jėgą ir šios jėgos vidutinis kvadratinis nuokrypis atitinkamai sumažėja.

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CUTTER CUTTING COBALT-RICH CRUSTS WITH WATER JET

S u m m a r y

Cobalt-rich crusts cutting method of cutter with water jet is proposed to reduce cutter impact load. Finite element model of cutter cutting cobalt-rich crusts with wa-

ter jet was established and surface initial crack forming conditions of cobalt-rich crusts were simulated. Simulation results show when water jet pressure is less than compressive strength of cobalt-rich crusts and water jet action point is not overlap with cutter action point, water jet can't reduce the minimum cutting force of cutter, which is used to form initial crack. When water jet action point is overlap with cutter action point, water jet can reduce the minimum cutting force effectively. When water jet pressure is greater than cobalt-rich crusts compressive strength, water jet can generate initial crack on cobalt-rich crusts surface alone. Experiments of cutter cutting cobalt-rich crusts simulation material with water jet were carried out. Experimental results show when water jet action point is not overlap with cutter action point, water jet can't reduce the maximum impact load of cutter, but it can reduce the root mean square of impact load. When water jet action point is overlap with cutter action point, water jet can reduce the maximum impact load dramatic and the root mean square of impact load is decreased accordingly.

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