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Wear Characteristics of TBM Disc Cutter Ring Sliding against Different Types of Rock

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ABSTRACT

To investigate wear characteristics of tunnel boring machine (TBM) disc cutter rings interacting with types of rock, a range of wear tests were performed on a TBM cutter test rig, and laboratory-scale disc cutters were used in the experiments. The mass loss, vertical load, temperature field, wear mechanism and change rule of cutter tip for the disc cutter rings were obtained during the tests. The results indicate that the rock types and properties of rock exhibit great influences on the cutter wear. The variation of the weight loss testing with different types of rock is partially explained by the discrepancies of vertical load, cutting temperature, and the transition of wear mechanisms. In addition, the test results show that the wear characteristics of cutter rings are mainly affected by uniaxial compressive strength (UCS) rather than equivalent quartz content (EQC) for types of rock. This study will benefit the design of cutter rings with enhanced wear resistance.

1. Introduction

Tunnel boring machine (TBM) is widely used in tunnel engineering due to its excellent tunneling performance and high safety (Geng et al., 2016; Zhang et al., 2018). Disc cutter is the key rock breaking component, which is installed on the cutterhead (Rostami, 2013; Choi and Lee, 2016). When breaking hard rocks, the cutter rings suffer from strong impact load, and severe wear, resulting in a high wastage of disc cutters and enormous economic loss. In a TBM project, the pecuniary loss associated with the cutter wear is about 1/5 of the excavation cost while the cutter replacement time accounts for nearly 1/3 of the total construction time (Zhang, 2010). Therefore, to develop the disc cutters performance, it is significantly necessary and attractive to reveal the wear characteristics of disc cutters on complicated geological conditions.

The wear characteristics of TBM disc cutters are influenced by a lot of factors, for instance the cutter properties, cutting parameters, rock types and rock properties (Rostami et al., 2014; Macias et al., 2016; Zhou et al., 2019). The rock types and rock properties are the key factors to affect the cutter wear characteristics during the cutting process (Li et al., 2020). To reveal the rock abrasiveness and the influences of rock properties on the abrasive wear of cutter rings, several test methods and indices were proposed, including the laboratoire central des ponts et chaussées (LCPC) test, Cerchar test, and Abrasion Value Steel test. The Cerchar Abrasivity Index (CAI) determined by the Cerchar test is a common criterion to evaluate the abrasiveness of rocks (Alber, 2008). Plinninger et al. (2003), Er and Tuğrul (2016), and Capik and Yilmaz (2017) revealed the effects of rock properties on CAI value through the Cerchar tests. Moradizadeh et al. (2016) revealed the correlations of equivalent quartz content and rock types with CAI. Alber (2008) reported the rock abrasivity is largely influenced by the ground stress. Abu Bakar et al. (2016) studied the impact of rock water content on CAI and found that CAI measured on saturated rock surface is less than that measured on the dry rock surface. Yaralı and Duru (2016) studied the effects of scratch length and surface condition on rock abrasiveness. However, the Cerchar test is not put forward for the studies of the TBM cutter wear at first, which has defects in demonstrating the cutter wear characteristics. Moreover, since the Cerchar test only reveals the wear characteristics of steel pin and the abrasiveness of rock under a specified load (70 N) from a macroscopic view, it fails to explain the difference of rock abrasiveness essentially as well as the influences of specific rock performances on the cutter wear.

The above studies are primarily focused on the rock abrasiveness rather than the disc cutter wear characteristics. Some related studies were also performed by researchers for cutter wear

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behaviours. Lislerud (1997) concluded the fundamental wear mechanisms for the disc cutter wear, that is the tribo-chemical reaction, fatigue, adhesive and abrasive wear. Lin et al. (2017) investigated the wear mechanisms and matching characteristics of disc cutters and rocks. Barzegari et al. (2015) proposed the primary wear mechanisms of the disc cutter are abrasive wear, adhesive wear and impact wear. The abrasive wear, induced by hard particles scratching the cutter ring surfaces, is the most commonly observed wear mechanism (Lislerud, 1997; Petrica et al., 2013, 2014).

The previous mentioned studies have promoted the comprehending of the rock abrasiveness and the cutter wear behaviours. However, the wear characteristics of disc cutters interacting with different rocks were still seldom studied in detail. In our previous work (Lin et al., 2017), we mainly discussed the influences of cutter ring mechanical performances on its wear resistance. Generally, the rock conditions encountered by TBMs are complex and changeable, hence the wear characteristics of the disc cutter may show significant differences under different kinds of rock conditions. Therefore, in this paper, five rock samples with different mechanical properties were chosen to slide against the cutter ring samples based on a bespoke test rig. Then, the relationship between the cutter wear characteristics and the rocks were preliminarily studied.

2. Material and Method

2.1 Experimental Set-Up

The wear experiments are conducted on a bespoke test rig, as illustrated in Fig. 1(a). The test rig includes hydraulic system, testing system and cutting system. The cutting system is illustrated in Fig. 1(b). Cutter ring is fixed on the cutter shaft through a key connection. The cutting position and penetration depth of disc cutter are achieved through lateral and vertical cylinder, respectively. Meanwhile, a positioning mechanism is adopted to ensure a constant cutting depth for the cutter ring in the wear test. Rock sample applied for experiments is placed in a steel box to restrict its freedom. The feed movement of the rock

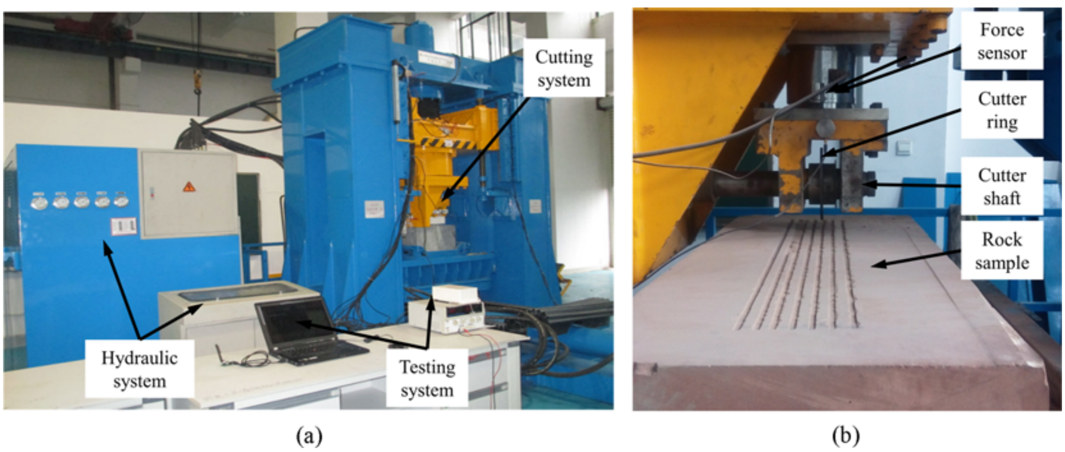

Fig. 1. Test Bench for Wear Experiments: (a) Overall Test Bench, (b) Cutting System

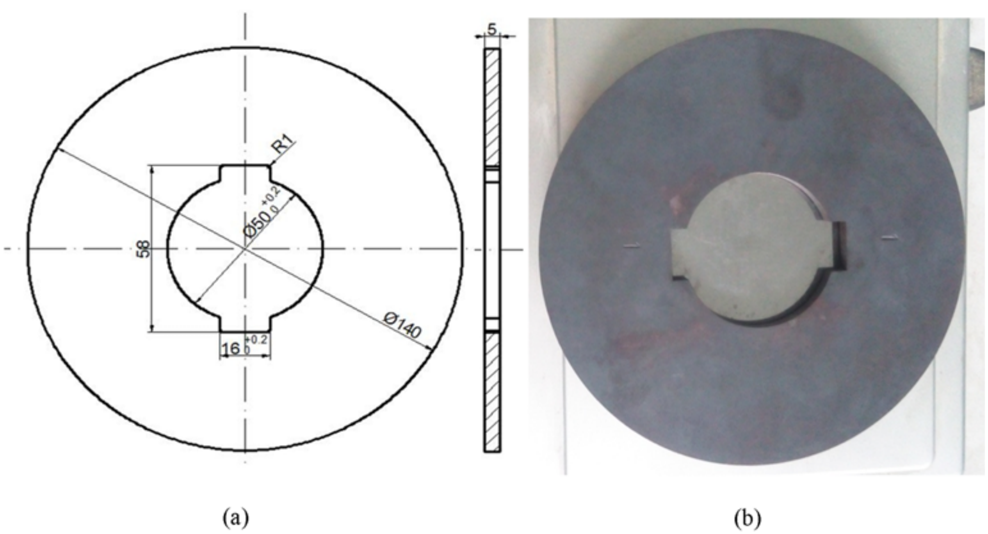

Fig. 2. Cutter Ring Sample: (a) Size and Shape, (b) Specimen

Table 1. Chemical Composition of Cutter Ring Sample (%)

C	Si	Mn	Cr	Mo	V	Fe
0.52	0.96	0.30	5.03	1.23	0.92	balance

Note: C, Si, Mn, Cr, Mo, V, and Fe represent carbon, silicon, manganese, chromium, molybdenum, vanadium, and ferrum, respectively.

is achieved by the longitudinal hydraulic cylinder.

2.2 Cutter Ring Sample

Considering the operability of the experiments, laboratory-scale cutters were applied instead of the full-scale 19-inch cutter rings, depicted in Fig. 2. Raw material of the cutter specimen is H13, the same material for an actual cutter ring (Yang et al., 2018), and its chemical composition is listed in Table 1. Cutter samples were annealed, quenched and tempered on the basis of heat treatment processes of an actual disc cutter ring, and the hardness and impact toughness are 55.5 HRC and 6.7 J/cm^2, respectively.

2.3 Rock Sample

On the basis of the TBM geological conditions (Ribacchi and Fazio, 2005; Wang et al., 2015), five typical rock samples, of which 3 rock types, obtained from field sites were used to slide against the cutter ring samples, including sandstone, rust stone, granite-1, granite-2, and gneiss, as shown in Fig. 3. The sandstone is a homogeneous rock with red grains and high porosity. The rust stone, granite-1and granite-2 are white to light gray and dense coarse crystalline rocks. The gneiss is a grey, fine, homogeneous and compact rock. The rock properties are listed in Table 2. The UCS and EQC are the basic rock properties which reflect the rock strength and mineralogical composition, respectively, both of which are closely related to the rock abrasiveness (Jiang et al., 2019, 2020). Thus, the effects of UCS and EQC on the disc cutter wear characteristics are investigated in this paper. Rock specimens are cut into the sizes of 900 × 380 × 260 mm^3 to fit the steel box.

2.4 Experimental Procedure

The cutting depth of disc cutters is generally kept at a constant value in the TBM excavation process (Wang et al., 2012, 2015). Therefore, the penetration of the cutter specimen was also preserved at a constant value in the wear tests. The contact stress between the cutter blade and rock is a critical factor to the wear

Table 2. Properties of Rock Samples

Rock	Elastic modulus (GPa)	UCS (MPa)	Tensile strength (MPa)	Density (g/cm^3)	EQC (%)
Sandstone	23.1	53.9	3.66	2.23	62.60
Rust stone	30.3	76.8	5.95	2.44	56.03
Granite-1	11.8	100.5	5.67	2.66	42.00
Granite-2	58.0	122.0	5.89	2.43	53.54
Gneiss	62.5	145.2	6.72	2.52	41.39

of disc cutter (Archard and Hirst, 1956; Gu et al., 2017). To restore the contact stress as the actual cutter ring and rock, the experiments were performed on the basis of the Hertzian simulation theory (Wang et al., 2013, 2014), as illustrated in Eq. (1). Because it is very difficult to obtain the cutter tip stress both in the lab and in-situ, a theoretical model (Rostami, 1993, 2013) was employed to acquire the stress, listed as Eqs. (2) and (3). Test parameters can be set using Eq. (4) for a specific rock in view of Eqs. (2) and (3):

$$(P)_{lab} = (P)_{field} , \tag{1}$$

$$P = C\sqrt[3]{\frac{S}{\varphi\sqrt{RT}} \cdot \sigma_c^{\,2}\sigma_t} , \tag{2}$$

$$\varphi = \cos^{-1}\left(\frac{R-h}{R}\right), \tag{3}$$

$$\frac{S}{\varphi\sqrt{RT}} = \frac{s}{\varphi'\sqrt{rt}}, \tag{4}$$

where $(P)_{lab}$ is the laboratory contact stress, $(P)_{field}$ is the in-situ contact stress, P denotes the basic stress of the contact zone, φ denotes the contact angle between cutter ring and rock, C denotes the dimensionless coefficient, R denotes the radius of an actual disc cutter, T denotes the tip width of the disc cutter, h denotes penetration, S is cutter spacing, σ_c is rock UCS, σ_t denotes the rock tensile strength, φ' denotes the contact angle for the cutter sample, r denotes the radius of the sample, t denotes the tip width of the sample.

Generally, 19-inch cutter with a tip width of 19.05 mm is widely employed in TBM project. The cutting penetration and the average cutter spacing are usually controlled at approximately 8 mm and 80 mm, respectively. In the experiments, the diameter

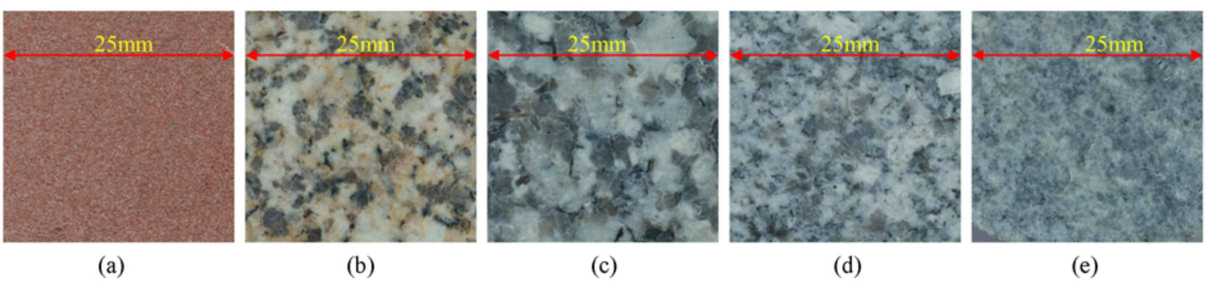

Fig. 3. Rock Samples: (a) Sandstone, (b) Rust Stone, (c) Granite-1, (d) Granite-2, (e) Gneiss

and the tip width of the cutter sample are 140 mm and 5 mm, and the cutter spacing was controlled at 15 mm. According to Eq. (4), the cutting depth of the sample was set to about 1 mm in the tests. Meanwhile, considering the vibration, the average cutting speed was determined as 6.7 mm/min while cutter rotating speed was controlled at about 20 r/min. The cutting length was controlled at 800 mm and the test lasted for 2 hours. During the tests, the cutting force and the temperature field were obtained by the three directional force sensor and the FLUKE Ti300 infrared thermal imager (measuring range: -20°C to +650°C, measurement error: ±2%), respectively. After the wear tests, the debris was gathered up and the wear loss of cutter was obtained by a high precision balance. Furthermore, the cutter ring worn surface was observed by KEYENGE VK-X100 microscopic apparatus.

3. Results

3.1 Wear Loss and Cutting Force

Figure 4 demonstrates the wear loss for the cutter samples testing with types of rock. From Fig. 4(a) the rock types exhibit a great effect on the cutter wear. The mass loss of the cutter sliding against sandstone is the least while the cutter ring interacting with gneiss suffers the severest abrasive wear. The weight losses of cutter rings testing with sandstone, rust stone, granite-1, granite-2, and gneiss are 0.33 g, 14.73 g, 18.42 g, 30.14 g and 54.6 g, respectively. The weight loss of the cutter testing with gneiss is about 165 times larger than that of the cutter cutting with sandstone. The relationships between mass loss and rock properties (UCS and EQC) are illustrated in Figs. 4(b) and 4(c). As depicted in Fig. 4(b), the weight loss increases obviously with the increase of UCS. However, with the increase of EQC, the mass loss shows some volatility and exhibits a decreasing trend on the whole, shown in Fig. 4(c).

Figure 5 exhibits the vertical force of the cutter samples testing with types of rock. It can be found that the variation of the vertical force for cutter samples cutting with different rock is similar to the change of the mass loss. When sliding against the gneiss, the cutter ring exhibits the largest vertical force of 10.48 kN, while the cutter ring sliding against sandstone presents the least vertical force of 4.52 kN. From the viewpoint of the rock properties, the vertical force increases with the increase of UCS as presented in Fig. 5(b), while the force decreases with the increase of EQC in general and shows some volatility as depicted in Fig. 5(c).

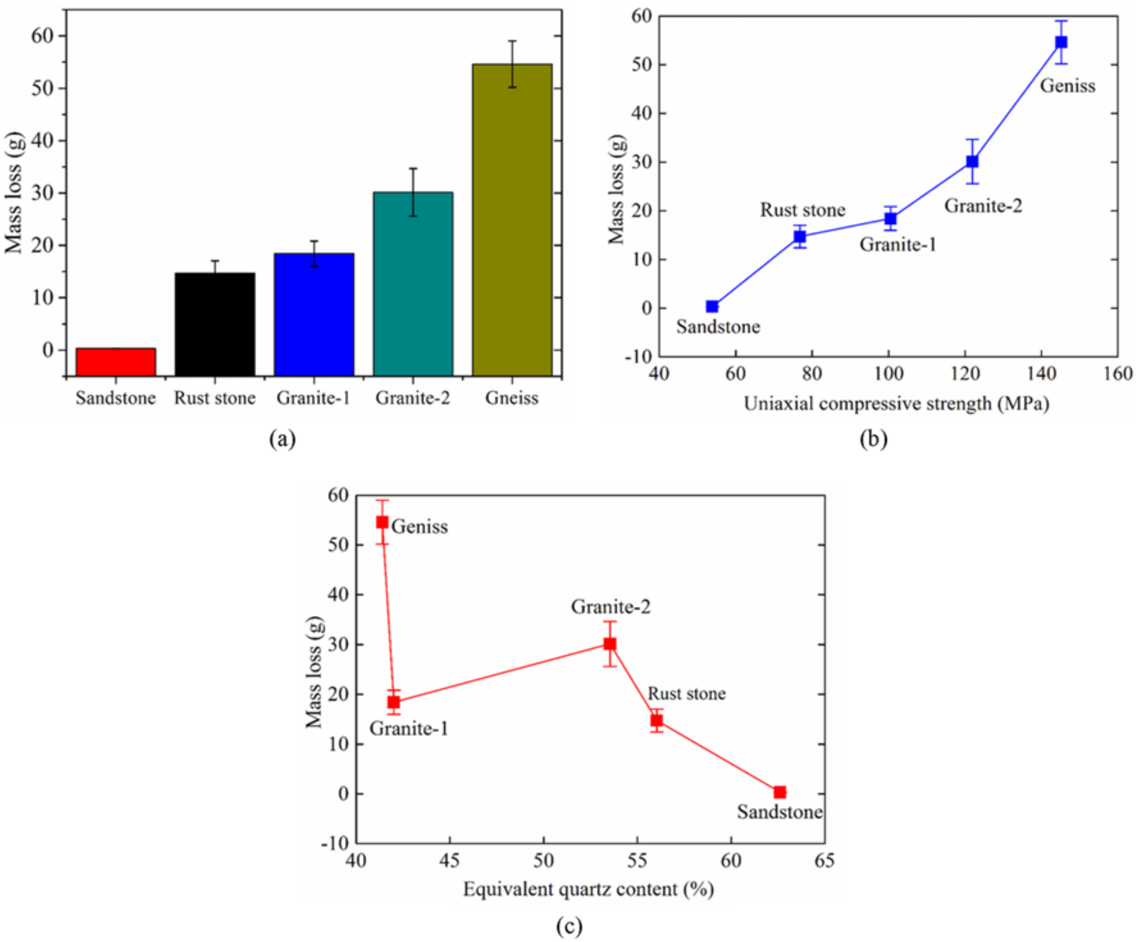

Fig. 4. Relationships between Mass Loss of Cutter Rings, Rock Types and Rock Properties: (a) Mass Loss with Rock Types, (b) Mass Loss with UCS, (c) Mass Loss with EQC

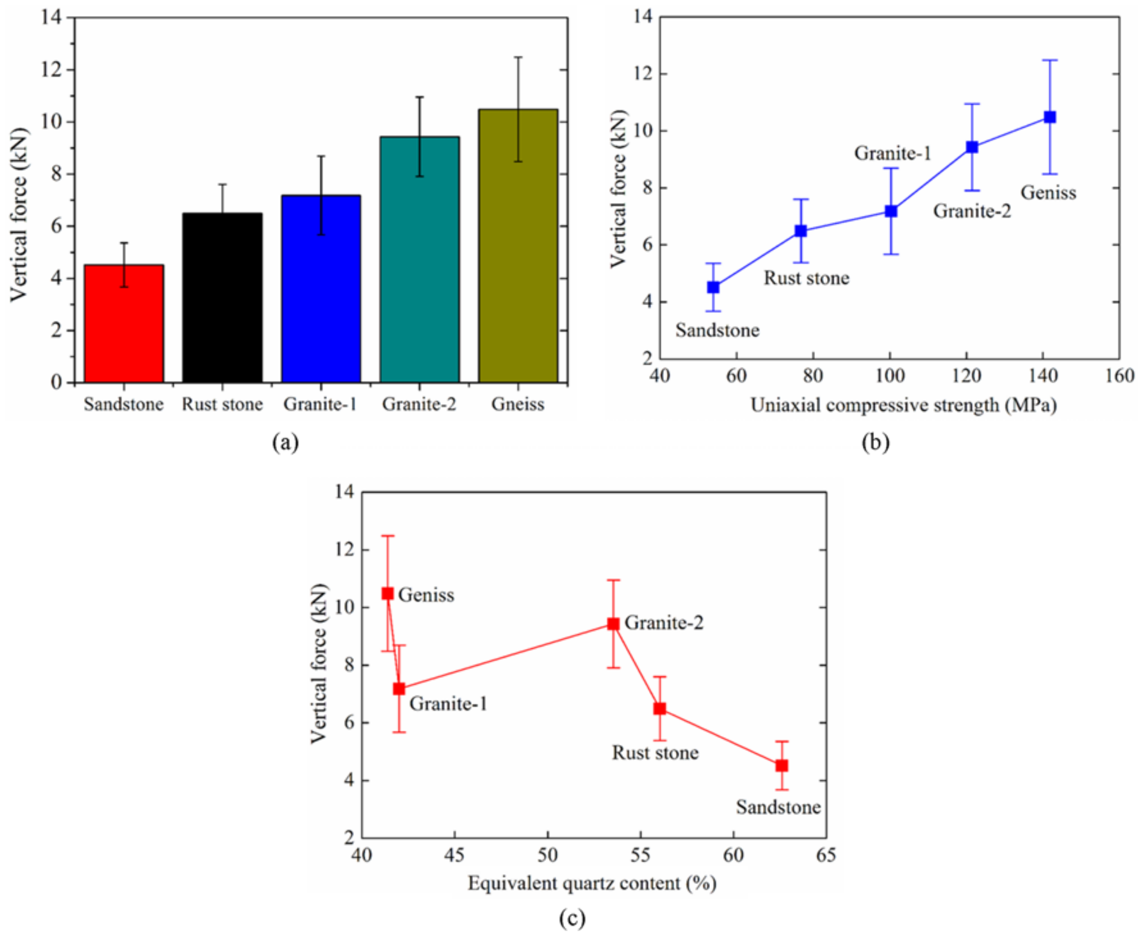

Fig. 5. Relationships between Vertical Force of Cutter Rings, Rock Types and Rock Properties: (a) Vertical Force with Rock Types, (b) Vertical Force with UCS, (c) Vertical Force with EQC

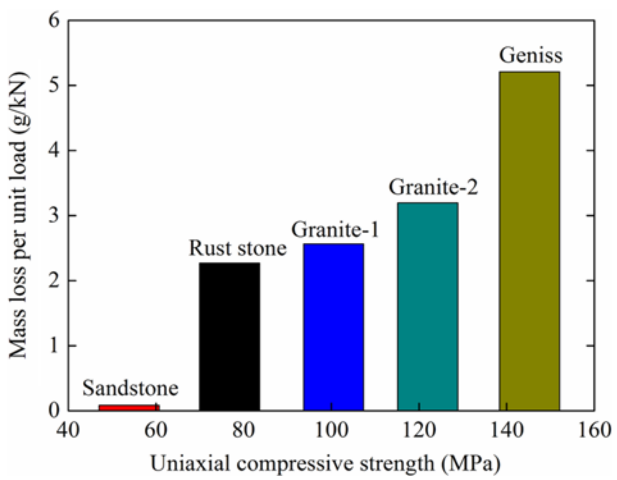

Fig. 6. Relationship between Mass Loss per Unit Load and UCS

According to the above analysis, both the mass loss and the cutting force of cutter rings increase significantly with the increase of UCS. To identify the abrasiveness of rock samples, the mass loss per unit load is calculated, as shown in Fig. 6. The mass loss per unit load increases with the increase of UCS for types of rock, which further confirms that the UCS is the main and key factors to affect the rock abrasiveness, i.e., comparing with EQC, the UCS is the more important factor for types of rock to dominate the wear behaviours.

3.2 Temperature Variation

The stable temperature distribution of the cutter samples testing with rocks is presented in Fig. 7, from which it is found that the temperature on the cutter is apparently higher than other parts. The highest temperature is displayed at the contact area of the cutter and rock due to the friction heats generated at this area. Average values of stable temperatures sliding against sandstone, rust stone, granite-1, granite-2, and gneiss are 163.5ºC, 199.2ºC, 217.5ºC, 246.6ºC and 293.5ºC, respectively, as presented in Fig. 8. The stable temperature of the specimen testing with gneiss is nearly 1.8 times larger than that of the cutter cutting with sandstone. The highest temperature of the cutter rings increases linearly with the increase of UCS, and is proportional to the weight loss, indicating that the cutter-rock wear temperature has a noticeable impact on the cutter wear characteristics.

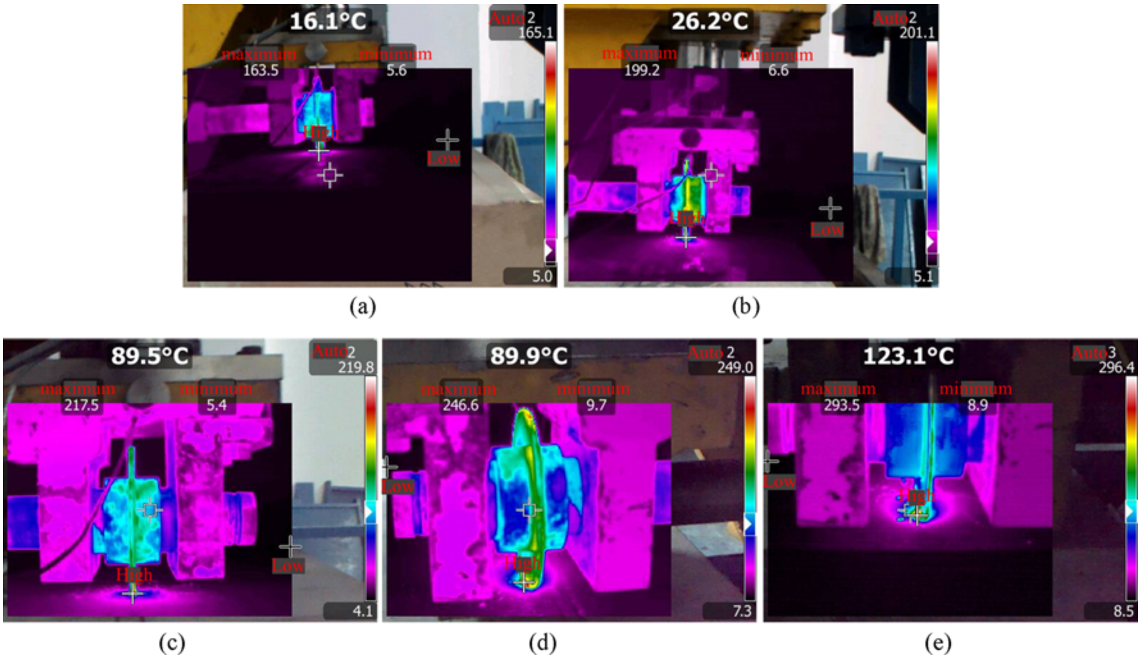

Fig. 7. Temperature Field of Cutter Samples Testing with Different Rock: (a) Sandstone, (b) Rust Stone, (c) Granite-1, (d) Granite-2, (e) Gneiss

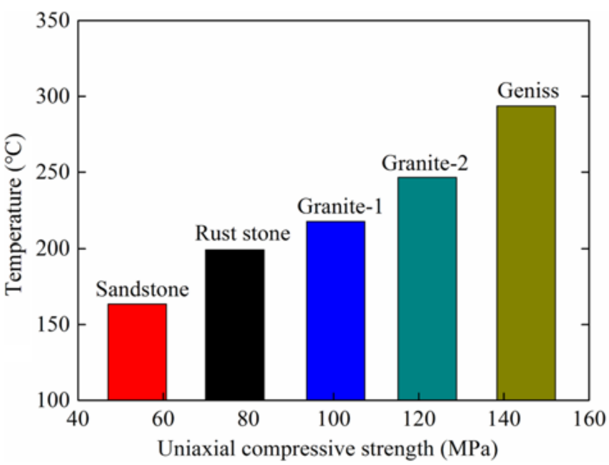

Fig. 8. Highest Temperatures of Cutter Samples Testing with Different Rock

3.3 Wear Mechanism

The worn surfaces of cutter rings are shown in Fig. 9, from which obvious scratches and furrows can be observed on all worn surfaces and the wear mechanisms vary with the rock types and rock properties. Sliding against sandstone, the cutter worn surface morphology is observed as slight microcosmic cutting with narrow and shallow grooves from Fig. 9(a). The cutting surface of the cutter sliding against rust stone also exhibits micro cutting. Nevertheless, the cutting grooves observed in Fig. 9(b) is relatively deeper than those of the cutter ring sliding against sandstone, which indicates that the abrasiveness of rust stone is stronger than that of sandstone at the same cutting depth.

Both ploughing and micro cutting can be found on the worn surfaces of the cutters cutting with granite-1, granite-2, and gneiss, indicating that the materials of the cutter tips are ploughed beside the grooves or cut away from the worn surfaces, as presented in Figs. 9(c), 9(d) and 9(e). The wear of the cutter testing with gneiss is the severest comparing with that of cutters cutting with granites. Additionally, it is concluded from Fig. 9 that the rock with low UCS mainly causes micro cutting in the process of wear tests, whereas the rock with high UCS leads to both ploughing and micro cutting, and the larger the UCS is the more serious the ploughing phenomenon occurs.

To further confirm the wear mechanism of the disc cutter testing with types of rock, the SEM analysis are carried out and shown in Fig. 10. Due to the weak abrasion ability of the sandstone, the surface of the cutter ring is relatively smooth, demonstrating only shallow groove marks and slight microcosmic cutting, as presented in Fig. 10(a). Since the abrasion ability of granite is stronger than that of sandstone, the surface of the cutter sliding against the granite shows a deeper groove, and a weak furrow phenomenon is discovered which bring an increase in the cutter mass loss, as presented in Fig. 10(b). Because the gneiss rock sample has the highest UCS compared with other rocks, the bond strength between the hard particles inside the rock mass is largest and the hard particles are easiest to embed into the cutter ring surface. When testing with gneiss, the cutter ring surface presents deepest wear scars and obvious material accumulation, as presented in Fig. 10(c). The maximum width of the cutting groove is more than 200 μm. The wear mechanisms of the cutter testing with gneiss manifest in severe microcosmic cutting and ploughing. The results of SEM analysis are basically consistent with those of laser microscope.

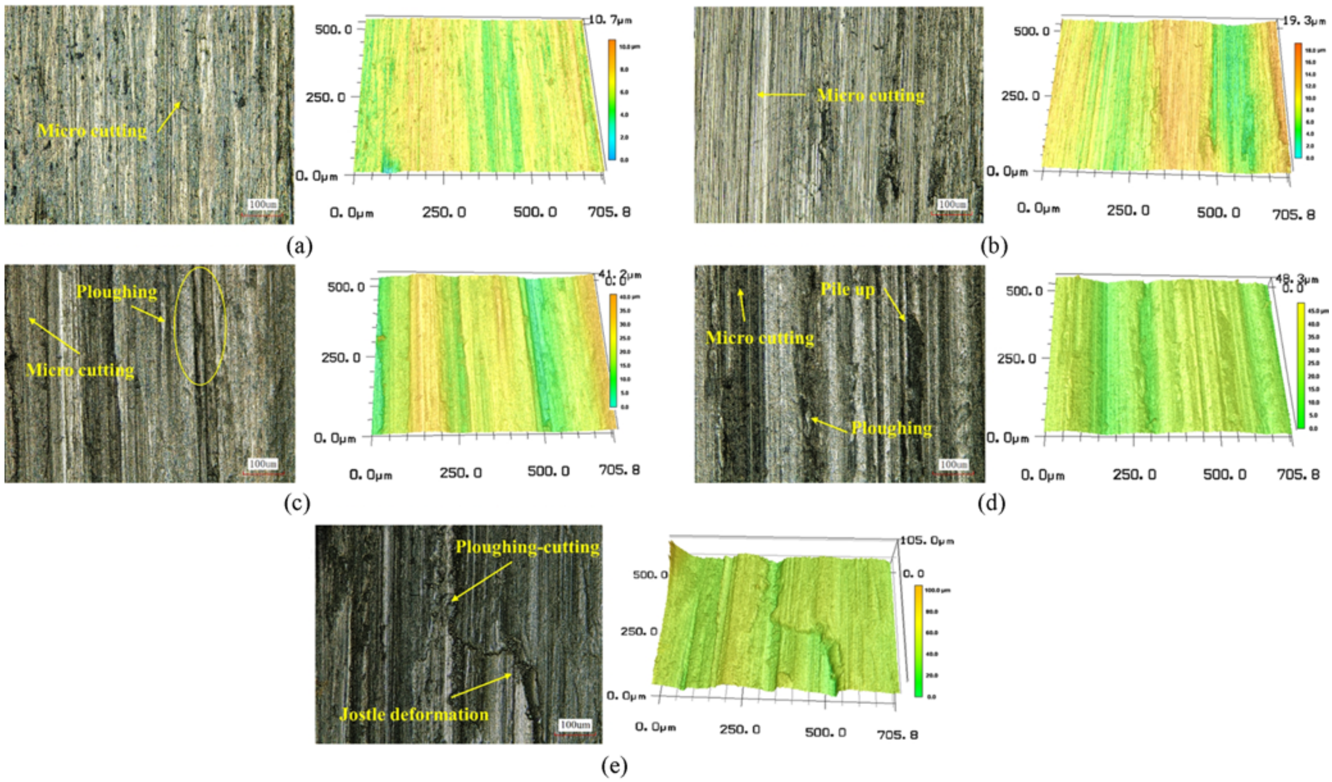

Fig. 9. Worn Surfaces for Cutter Rings Testing with Types of Rock: (a) Sandstone, (b) Rust Stone, (c) Granite-1, (d) Granite-2, (e) Gneiss

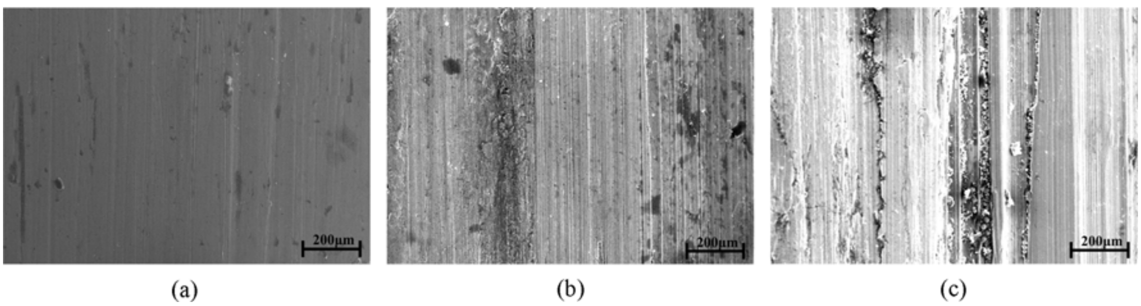

Fig. 10. SEM Images of Cutter Rings Testing with Types of Rock: (a) Sandstone, (b) Granite, (c) Gneiss

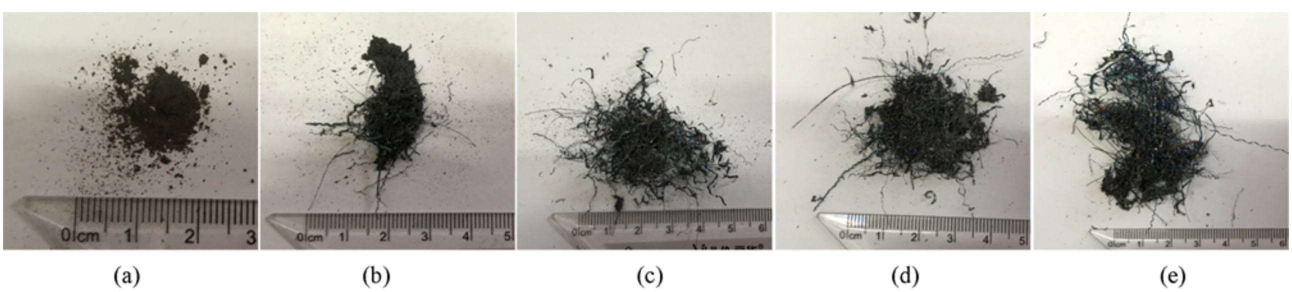

Fig. 11. Wear Debris of Cutter Rings Testing with Types of Rock: (a) Sandstone, (b) Rust Stone, (c) Granite-1, (d) Granite-2, (e) Gneiss

3.4 Wear Debris and Wear Depth

A magnet is used to gather up the wear debris after wear tests, the debris is illustrated in Fig. 11. For sandstone the wear debris emerged in the test is mostly powders while that of cutter sample cutting with rust stone is mainly powders with a few of filaments produced by the significant micro cutting. For granite-1, granite-2, and gneiss, a large number of long filaments can be observed among the wear debris due to the strong rock abrasiveness. In addition, the wear debris from the gneiss test is longer and wider than that produced by granite-1 and granite-2, and the size of the

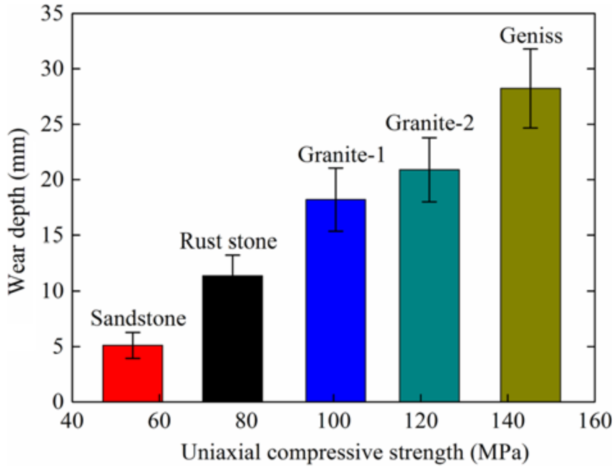

Fig. 12. Variation of Wear Depth for Cutter Ring Sliding against Types of Rock

longest debris created by gneiss is larger than 60 mm, as depicted in Fig. 11(e).

As presented in Fig. 12, the average wear depths of cutter rings testing with sandstone, rust stone, granite-1, granite-2, and gneiss were obtained by the laser microscopic measurement apparatus, which are 5.11 mm, 11.38 mm, 18.19 mm, 20.89 mm and 28.23 mm, respectively. The wear depth testing with gneiss is the largest compared with those of cutter rings testing with the others, which is approximately 5.5 times larger than that of the cutter cutting with sandstone. Since the rock abrasiveness is improved with the increase of UCS for types of rock, the hard particles stab into the cutter ring surface and cut away the material easier while the cutter ring slides against the rock with a higher UCS. Additionally, because the cutter ring sample has a relatively low hardness and a high toughness, the wear debris produced on the cutter surface is not easy to break when the wear depth is at a high level, resulting in long threadlike wear debris.

3.5 Variation of Cutter Tip

After wear tests, the variations of the cutter ring tips were observed and illustrated in Fig. 13, and it is found from the figure that the shape of worn cutter tips varies with the rocks. When sliding against the sandstone, the shape of worn cutter tip exhibits almost no change due to the weak abrasiveness of rock. Similarly, the cutter tip shape changes a little when sliding against

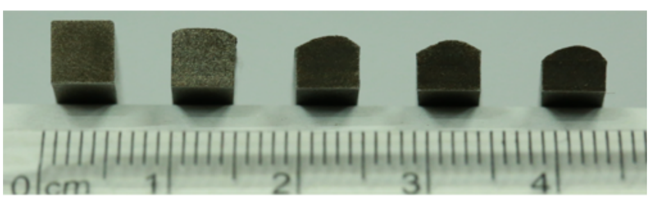

Fig. 13. Shape of Cutter Tips for Cutter Rings Sliding against Types of Rocks: (a) Sandstone, (b) Rust Stone, (c) Granite-1, (d) Granite-2, (e) Gneiss

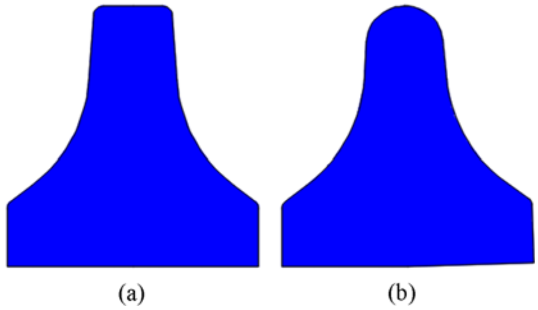

Fig. 14. Common Profile of Disc Cutter: (a) Flat Cutter Tip, (b) Arc Cutter Tip

the rust stone. The shapes of worn cutter tips for cutter rings testing with granite-1, granite-2 and gneiss change obviously due to the enhancement of the rock abrasiveness. The variability of the cutter tip shape increases significantly with the increase in UCS for types of rock in general. It should be noted that the shape of worn cutter tips sliding against the rock with high UCS is gradually transforming to a circular shape which means the abrasive wear on the edge of cutter tip is more severe than that in the middle part of cutter tip, i.e., the stress distribution on the tip is unbalanced and the stress on the edge of cutter tip is greater than that in the middle part.

Generally, there are two kinds of cutter tip shape for the commonly used disc cutter including flat cutter tip and arc cutter tip (Fig. 14). Compared with the arc cutter tip, the rock breaking volume per unit time produced by the flat cutter tip is higher due to its larger contact area with rocks. In the TBM tunneling process, it is expected that the shape of cutter tip changes as little as possible after the cutter wear so as to keep a stable cutting force for the disc cutter and cutterhead (Balci and Tumac, 2012; Tumac and Balci, 2015; Zhang et al., 2014). Since the shape of cutter tip changes little after wear when cutting the rocks with low UCS, the flat tip is suitable for the above-mentioned geological conditions so that a relatively constant tip profile can be retained and cutterhead thrust will be kept stable for a long time in tunneling. However, when the disc cutters break rocks with high UCS such as granite-1, granite-2, and gneiss, it is suggested from the preceding analysis that the arc cutter tip may be a better option due to the significant shape changes on the edge of cutter rings.

4. Discussion

Wear characteristics of cutter samples vary with the rock types, and the immediate reason for the difference in weight loss of cutter samples cutting with different rocks is the discrepancies of vertical force and temperature field, concluding from section 3.1 and 3.2. The mass loss increases with the increase of vertical force as depicted in Figs. 4 and 5. Due to the constant penetration, the larger the vertical force the larger the contact stress. The large vertical force favours a relatively deep abrasive indentation and wide furrow on the worn surface, leading to severe wear. As stated above, the mass loss is proportional to the highest temperature of cutter rings. During the wear tests, the friction heats mainly gather at the cutter-rock contact area, and obviously, the higher the temperature is the more energy converts into friction heats. On the other hand, the rise of cutter tip temperature further deteriorates the cutter wear. Since the cutter worn surfaces soften gradually with the increase of temperature, hard particles can pierce into and cut materials away from the cutter surfaces easily, and thus the depth and width of the grooves as well as the mass loss increase with the increase of cutter temperature (Fig. 9). In addition, the oxidation (Wei et al., 2011) and thermal stress of the cutter worn surfaces caused by the high temperature are also the reason for the rise in the mass loss.

The fundamental reason for the variation of the mass loss is the transformation of the wear mechanisms. The main wear mechanisms of cutter rings sliding against sandstone and rust stone are slight micro cutting with shallow scratches owing to the weak rock abrasiveness, causing a relatively low wear depth and small wear loss. The wear debris of cutter rings is primarily composed of powders. The predominate wear mechanisms of cutter rings sliding against granite-1, granite-2 and gneiss are severe ploughing-cutting plastic deformation, and the ploughing grooves and pile ups can be observed significantly on the worn surfaces, resulting in a high wear depth and large mass loss. The wear debris of cutter rings changes from powders to some long filaments due to the serious material removal. The above analysis indicates that serious ploughing is the main reason for the increase of the cutter wear loss.

From the viewpoint of rock properties, it is found from section 3 that the UCS is a relevant factor for the difference in the cutter wear characteristics. The mass loss, rock breaking force and temperature of the cutters increase with the increase of UCS. The wear mechanism is transformed from slight microcosmic cutting to severe ploughing and microcosmic cutting with the raise of UCS. A flat cutter tip is more favourable when cutting the rock with low UCS, while the arc cutter tip is more preferred to maintain a relatively stable cutting force for the disc cutter cutting the rock with high UCS. The influence of EQC on the rock abrasiveness is still controversial from a review of relevant literature. Generally, there are two entirely different perspectives on the effect of EQC on rock abrasiveness. Some researchers proposed that the EQC has a positive effect on the rock abrasiveness, namely, the increase of EQC linearly promotes the rock abrasiveness and exacerbates the wear of cutting tools (West, 1989; Yaralı et al., 2008). However, an opposite view was put forward by other researchers who deemed that there is limited or even non-existing correlation between the rock abrasiveness and EQC, or that the EQC is inversely correlated with the rock abrasiveness. Plinninger et al. (2003) mentioned that only EQC cannot represent the rock abrasiveness, and a similar conclusion was suggested by Thuro (1997). Ko et al. (2016) stated that quartz content is the less influencing factor to estimate the CAI value. In this work, it is indicated from the wear tests that the EQC is the less influencing factor comparing with UCS, and tends to show an inverse correlation with the rock abrasiveness in general, consisting with the second perspective. However, more tests are still needed to confirm the relationship between rock abrasiveness and EQC.

5. Conclusions

The investigations on the wear characteristics of the TBM disc cutters testing with types of rock through a series of wear experiments are presented in this study, and the conclusions are as follows:

1. The rock types and rock properties show significant influences on the disc cutter wear characteristics. The immediate reason for the difference of mass loss testing with different rock is the discrepancies of vertical force and temperature field, whereas the essential reason is the transformation of wear mechanisms. Additionally, the cutter wear characteristics are mainly affected by UCS rather than the EQC.
2. The weight loss sliding against sandstone is the least while that with gneiss is the largest. The variation tendency of the vertical force for cutter rings is the same as the mass loss. Both the mass loss and the cutting force increase with the increase of UCS.
3. During wear tests, the highest temperature is observed at the contact area of the cutter tip and rock sample. Stable temperature increases linearly with the increase of UCS for types of rock.
4. The cutter dominant wear mechanisms change from slight micro cutting to a combination of ploughing and micro cutting with the raise of UCS. Both the length of wear debris and wear depth increase with the increase of UCS for types of rock.
5. Based on the change rule of the worn cutter tip, the flat cutter tip can be used to cut the rocks with low UCS and the arc cutter tip can be employed to cut the rocks with high UCS to keep a constant tip shape and to maintain a relatively stable cutting force for the cutterhead.

Based on a bespoke test bench, we proposed a method to investigate the impact of rock type and rock properties on the cutter wear through a series of wear experiments, which truly reproduced the motion and wear characteristics of the disc cutter. The change rule of cutter wear and related influencing factors were preliminarily obtained, which can provide scientific guidance for the disc cutter design.

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