WEP
Warwick
Evans
Publishing

International Journal of Mechanical and Electrical Engineering
ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 3, Number 3, Year 2024
DOI: https://doi.org/10.62051/ijmee.v3n3.05
Journal homepage: https://wepub.org/index.php/IJMEE/index

Experimental Study on the Crushing Strength of Diamond Grains

Jianlin Yao, Bin Liu, Yong Li

CCDC Drilling & Production Technology Research Institute, China

ABSTRACT

This study investigates the crushing strength of single diamond grains of varying grades and particle sizes using the WDW-100 electronic universal testing machine. The research aims to understand the mechanical properties of diamond particles, which are critical for optimizing the performance of diamond tools in industrial grinding processes. High-grade diamond particles, characterized by their regular polyhedral shapes and minimal impurities, exhibit higher and more stable maximum load forces compared to medium- and low-grade particles. Medium-grade particles show a balance between strength and brittleness, while low-grade particles display significant variability in their structural integrity due to higher impurity levels and defects. The study also reveals that larger diamond particles tend to have lower average maximum load forces, attributed to increased crystal defects and pronounced grain boundary effects. These findings underscore the importance of considering both the grade and particle size of diamond grains in applications requiring high mechanical strength. The insights gained from this research are essential for improving the design and durability of diamond tools, ensuring their efficiency and longevity in industrial applications.

KEYWORDS

Diamond Particles; Strength; Coring Bit.

1. INTRODUCTION

The grinding of hard materials like sandstone is a fundamental process in various industrial sectors, such as construction, mining, and manufacturing. Sandstone, known for its high durability and hardness, presents substantial challenges during the grinding process[1,2]. These challenges arise primarily from the material's resistance to mechanical wear and its tendency to rapidly degrade conventional cutting tools. Overcoming these challenges is crucial for ensuring efficiency and precision in industrial operations that rely on grinding processes. One of the most effective solutions to these difficulties is the use of diamond tools, particularly surface-set coring bits[3]. These tools have gained widespread popularity due to their exceptional hardness and wear resistance, which make them highly suitable for cutting through tough materials like sandstone[4–6].

Diamond tools, specifically those that incorporate single diamond grains embedded in their surface, are particularly valued in industrial grinding processes. Their high hardness, combined with their ability to retain sharpness over extended periods, allows them to perform under conditions that would quickly degrade traditional cutting tools[7]. The interaction between a diamond grain and sandstone during the grinding process is highly complex, involving a combination of mechanical forces and thermal effects. As the diamond grain engages with the sandstone, a variety of factors, such as the grain's strength, the applied load, and the material's thermal response, all influence the efficiency and quality of the grinding operation. The hardness of the diamond is particularly crucial, as it directly affects the cutting performance and longevity of the tool[8].

One of the key considerations in this process is the crushing strength of diamond grains, which is a critical factor in determining how well the diamond tool performs during grinding[9,10]. The crushing strength refers to the resistance of the diamond grain to mechanical failure when subjected to stress. A higher crushing strength indicates greater durability and a longer tool life[11,12]. However, various factors can affect the crushing strength of diamond grains, including diamond classification, grain size, crystal orientation, and the presence of impurities. The classification of diamonds, for instance, determines their quality and suitability for specific applications. Larger diamond grains, while potentially more durable, may not always provide the fine cutting precision required in certain operations[13]. Crystal orientation also plays a significant role, as certain orientations may exhibit greater strength and wear resistance than others. Impurities, even in trace amounts, can weaken the diamond grain, reducing its overall performance[14].

Although diamond tools are widely used for grinding hard materials like sandstone, there is still much to learn about the mechanical properties of the diamond grains themselves[15]. The crushing strength of these grains remains an area of active research due to the complex nature of their behavior under stress. Experimental studies play a crucial role in advancing our understanding of diamond grain performance. Through controlled experiments, researchers can investigate the mechanical properties of diamond grains under various grinding conditions, providing insights into how factors such as load, speed, and grain size influence their behavior. By conducting systematic experiments on the crushing strength of diamond grains, researchers can generate valuable data on the parameters that affect the durability and wear resistance of diamond tools[16]

This research is vital for optimizing the design and manufacturing of diamond tools. By understanding the mechanical limits of diamond grains, manufacturers can develop more efficient tools that offer improved performance and a longer lifespan. For example, selecting the optimal grain size and orientation for specific grinding tasks can enhance cutting efficiency while reducing wear and tear on the tool[17,18]. Furthermore, knowledge gained from studying diamond grain properties can inform the development of new diamond tool technologies, such as improved bonding methods or enhanced grain compositions, which could further increase tool performance. In conclusion, the use of diamond tools, particularly those with single diamond grains, is indispensable in the grinding of hard materials like sandstone. However, understanding the factors that influence the crushing strength of diamond grains is critical for improving tool design and optimizing grinding performance. Ongoing experimental research is essential to advancing our knowledge in this area, with the ultimate goal of enhancing the efficiency, durability, and lifespan of diamond tools in industrial applications[19,20]

2. EXPERIMENTAL SETUP

2.1. Sample Preparation

The diamond particles used in the experiment are categorized into three grades: high-grade, medium-grade, and low-grade. High-grade diamond particles exhibit a regular polyhedral shape with clear crystal edges and apexes, as shown in Fig 1. These particles have a high luster due to the absence of pits on their surfaces and contain few internal impurities. Most of these high-grade particles are octahedral in shape. The high-grade category includes a total of 10 particles, with sizes ranging from a minimum diameter of 2.8mm to a maximum of 3.6mm. These particles are further classified into three subcategories based on size: 2.8-3.0mm (6 particles), 3.1-3.3mm (2 particles), and 3.4-3.6mm (2 particles).

Fig 1. High-grade diamond particles

Medium-grade diamond particles also exhibit a regular polyhedral shape with relatively flat and smooth crystal faces, as shown in Fig 2. These particles show different colors due to varying internal elements and maintain a high luster. The majority of medium-grade particles are either octahedral or dodecahedral in shape. This category includes a total of 28 particles, with sizes ranging from a minimum diameter of 1.7mm to a maximum of 2.7mm. The medium-grade particles are classified into three subcategories: 1.7-2.0mm (11 particles), 2.1-2.4mm (13 particles), and 2.5-2.7mm (4 particles).

Fig 2. Medium-grade diamond particles

Low-grade diamond particles, on the other hand, mostly exhibit an irregular polyhedral shape with pits on their surfaces, resulting in low luster, as shown in Fig 3. Some of these particles have sharp edges, and a very few show a regular variant polyhedral shape. The low-grade category includes a total of 18 particles, with sizes ranging from a minimum diameter of 2.5mm to a maximum of 4.2mm. These particles are classified into three subcategories: 2.5-3.0mm (11 particles), 3.1-3.6mm (3 particles), and 3.7-4.2mm (4 particles).

Fig 3. Low-grade diamond particles

The detailed summary of the diamond particles utilized in the experiments is comprehensively presented in Table 1. This table provides an organized overview of the various grades of diamond particles, including their morphological characteristics, quantity, size distribution, and classification ranges. By systematically categorizing the diamond particles, the table serves as a crucial reference for understanding the specific attributes and quality of the materials used in the experimental setup.

Table 1. Summary of diamond particles for experiments

Grade	Morphology	Size distribution	Quantity (pieces)	Total
High		2.8-3.0mm	6	13
		3.1-3.3mm	2	
		3.4-3.6mm	2	
Medium		1.7-2.0mm	11	28
		2.1-2.4mm	13	
		2.5-2.7mm	4	
Low		2.5-3.0mm	11	18
		3.1-3.6mm	3	
		3.7-4.2mm	4	

2.2. Testing Apparatus

The apparatus used for the experiments is a WDW-100 universal material testing machine. This machine is capable of applying controlled loads to the diamond grains and sandstone samples, allowing for precise measurement of their mechanical properties. The universal material testing machine is equipped with advanced sensors and data acquisition systems to capture detailed information on the crushing strength and other relevant parameters of the diamond grains under various conditions. This setup ensures that the experimental data is accurate and reliable, providing valuable insights into the performance and durability of the diamond particles used in the grinding process.

Given the relatively small size of the diamond particles and the comparatively larger surface area of the upper and lower compression plates, the misalignment and friction between the traditional loader plates can significantly influence the load required to achieve the crushing strength of the diamond particles, as evidenced by the test results. To mitigate this issue and enhance the precision of the experiments, it was decided to replace the existing compression plates with ones that have a smaller contact area. This modification aims to minimize the effects of misalignment and friction, thereby improving the accuracy of the experimental measurements.

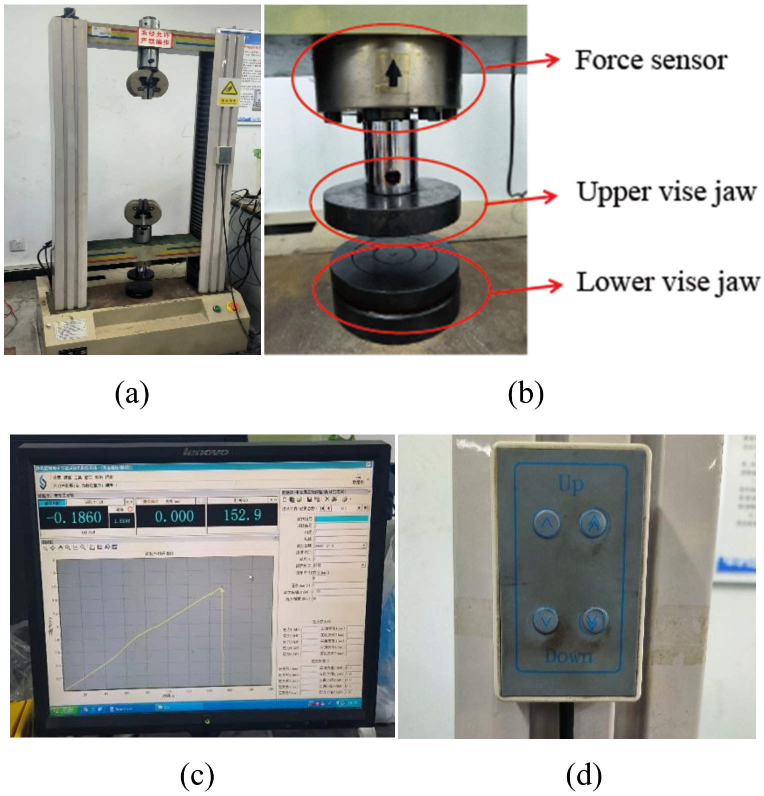

Fig 4. (a) WDW-100 universal material testing machine; (b) Loader (c) Data acquisition; (d) Control box

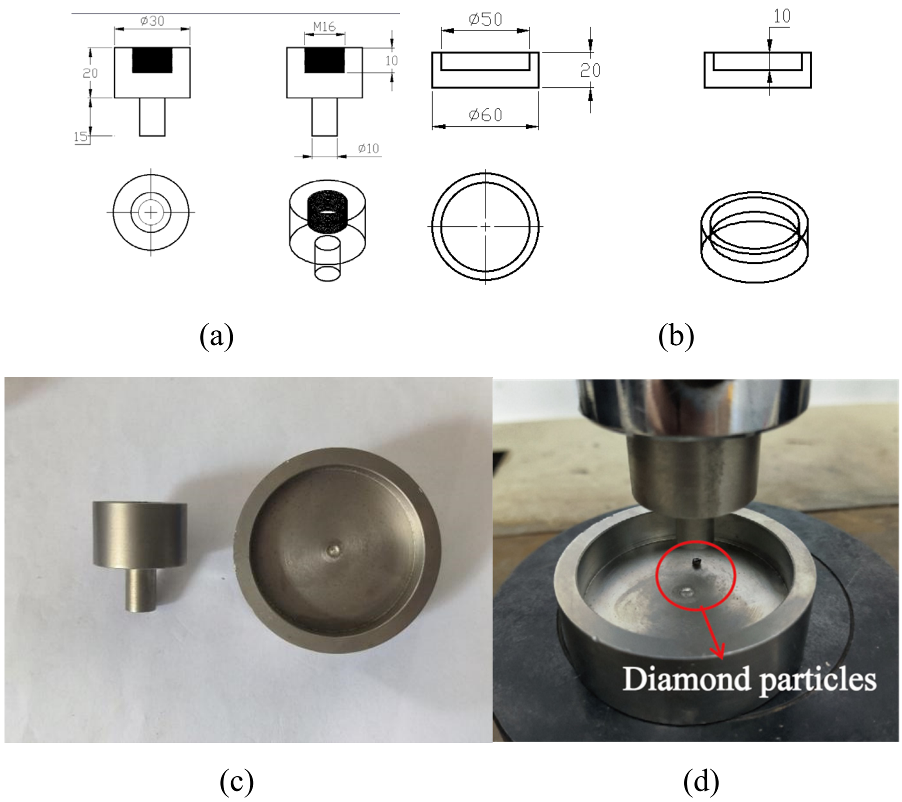

Fig 5. (a) Design of the Upper Compression Plate, (b) Design of the Lower Compression Plate, (c) Actual Compression Plates, (d) Relative Position Diagram

The design of the new compression plates is depicted in Fig 5 (a) and (b), while the actual plates are shown in Fig 5 (c) and (d). The new compression plates are fabricated entirely from 62 molybdenum-vanadium steel, a material renowned for its high strength and excellent impact resistance. This material selection ensures that the plates can endure the rigorous demands of the experiments, providing a stable and reliable platform for testing the crushing strength of diamond particles. The improved design and material choice are anticipated to significantly enhance the precision and reliability of the experimental results, thereby contributing to a more comprehensive understanding of the mechanical properties of diamond grains.

2.3. Experimental Procedure

The experimental procedure for measuring the crushing strength of diamond grains involves a series of carefully controlled steps to ensure accuracy and repeatability. The apparatus used for this experiment is depicted in Fig 5, which illustrates the setup of the pressure device. The lower compression plate is fixed, while the upper compression plate is controlled either manually via a remote control or through computer software. The objective is to apply pressure until the diamond particles are crushed, with the force-time curve displayed in the software. The simplified diagram of the experimental principle is shown in Fig 6.

The experiment follows the standard JB/T 10985-2020 for super-hard abrasive materials, which outlines the method for determining compressive strength. This standard ensures that the experimental procedure is consistent and reliable, providing a basis for comparing results across different tests and conditions.

During the experiment, data collection and processing are critical to obtaining accurate results. To minimize errors, a small number of diamond grains from the same batch are tested repeatedly, and the average value is taken as the compressive strength of the sample. The average load value P is calculated using the formula:

$$P = \frac{\sum_{i=0}^{n} P_i}{n} \tag{1}$$

where P_i is the peak load for each individual grain. This approach ensures that the results are representative of the batch and reduces the impact of any anomalies.

The experimental steps are as follows: First, single diamond grain samples are selected from pre-classified bags, and their initial dimensions, including particle size and mass, are measured. The surface of the sample stage on the pressure device is then adjusted, and the pressure sensor reading is zeroed. The stage is cleaned to ensure no foreign objects are present. Using tweezers, a single diamond grain is gently placed on the work stage beneath the pressure device, and its position is adjusted to ensure stability.

The pressure device is then turned on, and pressure is gradually increased. The state of the sample is monitored in real-time, and pressure readings are tracked through the software. When the diamond grain is crushed or can no longer withstand additional pressure, the pressure increase is stopped. The maximum pressure reading from the gauge, which represents the maximum static compressive strength of the diamond grain, is recorded. Throughout the experiment, the upper compression plate should move down slowly at a speed of 0.1 mm/min. The device will automatically stop when the maximum load is detected. The typical time evolution of load is shown in Fig 7. The experimental scenarios are shown in Table 2.

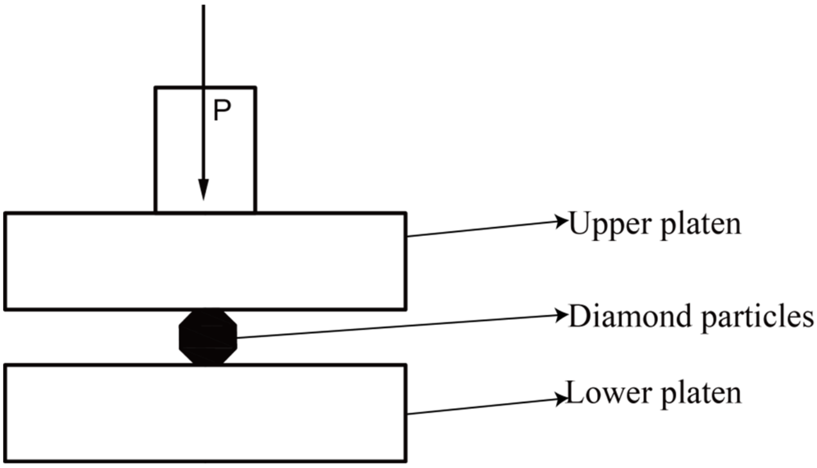

Fig 6. The simplified schematic of the experiment

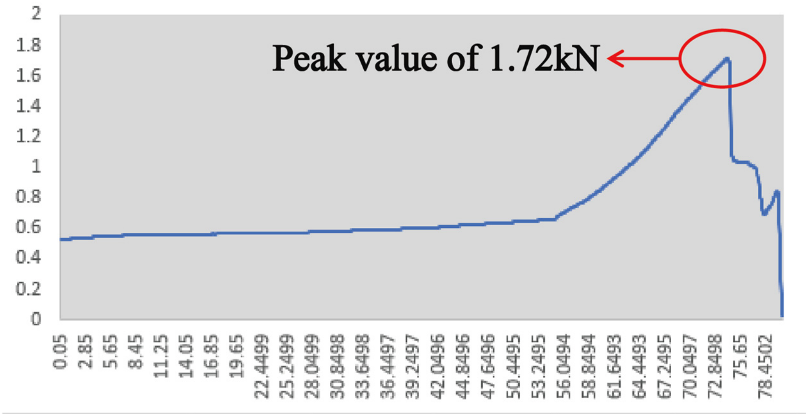

Fig 7. Typical time evolution of load

Table 2. Experimental scenarios

Label	Grade	Size	Quantity
1	High	2.8-3.0mm	4
2		3.1-3.3mm	2
3		3.4-3.6mm	2
4	Medium	1.7-2.0mm	4
5		2.1-2.4mm	4
6		2.5-2.7mm	4
7	Low	2.5-3.0mm	4
8		3.1-3.6mm	3
9		3.7-4.2mm	4

3. RESULTS AND DISCUSSION

Figures 8 through 10 display the experimental results for the high-grade diamond particle group. These figures provide a detailed account of the crushing strength tests performed on high-grade diamond grains, emphasizing the peak forces and corresponding particle sizes. Similarly, Figures 11 through 16 present the experimental results for the medium-grade diamond particle group. These figures offer a comprehensive overview of the crushing strength tests conducted on medium-grade diamond grains, highlighting the peak forces achieved and the particle sizes tested. Figures 14 through 19 illustrate the experimental results for the low-grade diamond particle group. These figures detail the outcomes of the crushing strength tests on low-grade diamond grains, including the peak forces recorded and the particle sizes involved. The data provided in these figures are essential for evaluating the mechanical properties and resilience of different diamond particles under compression.

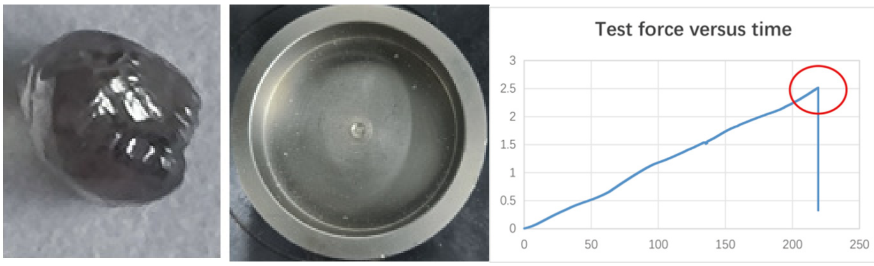

Fig 8. High-grade diamond. Particle Size: 2.8mm, Peak Test Force: 2.54kN

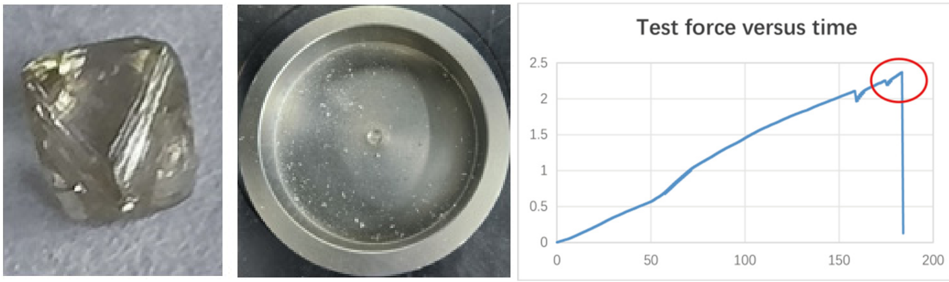

Fig 9. High-grade diamond. Particle Size: 3.2mm, Peak Test Force: 2.37kN

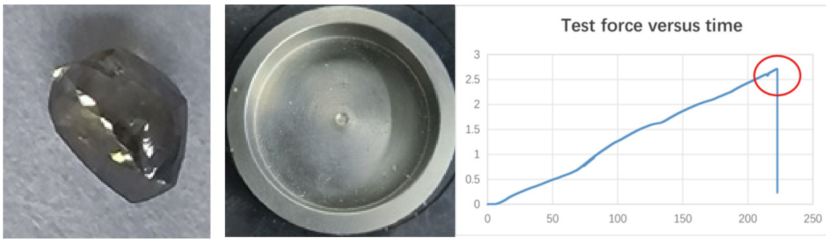

Fig 10. High-grade diamond. Particle Size: 3.6mm, Peak Test Force: 2.71kN

Fig 11. Medium-grade diamond. Particle Size: 2.0mm, Peak Test Force: 1.82kN

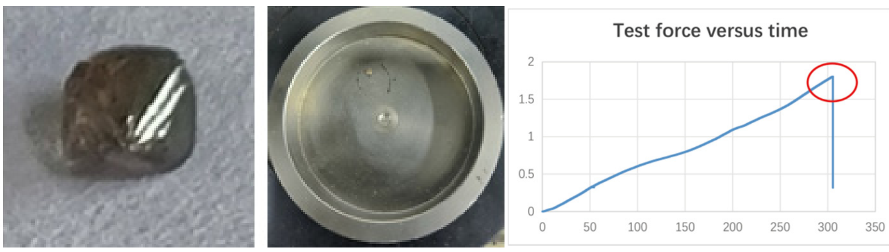

Fig 12. Medium-grade diamond. Particle Size: 2.2mm, Peak Test Force: 1.03kN

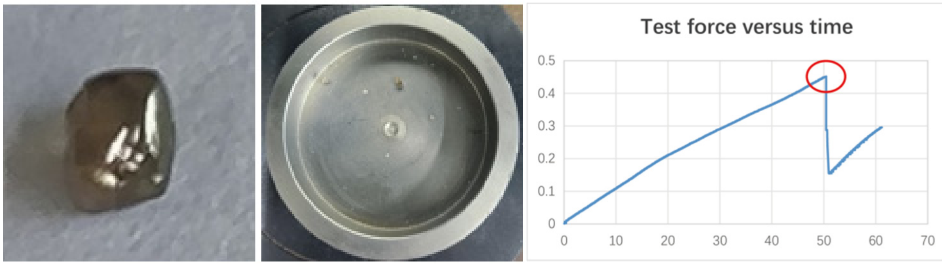

Fig 13. Medium-grade diamond. Particle Size: 2.6mm, Peak Test Force: 0.45kN

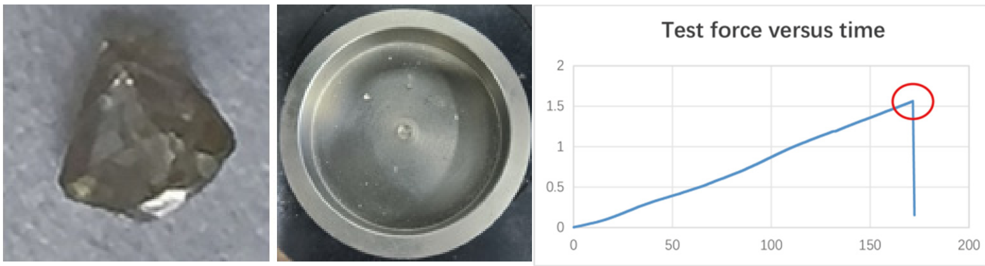

Fig 14. Low-grade diamond. Particle Size: 2.5mm, Peak Test Force: 1.56kN

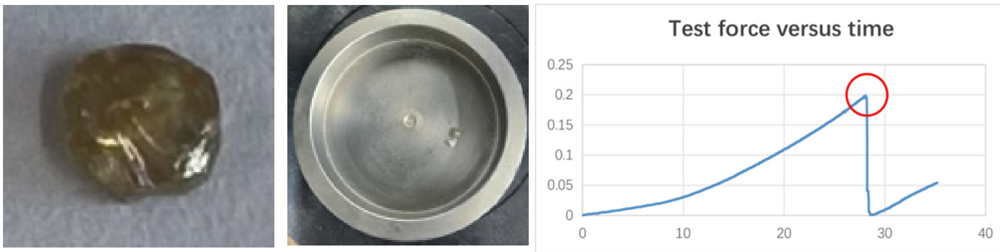

Fig 15. Low-grade diamond. Particle Size: 3.6mm, Peak Test Force: 0.20kN

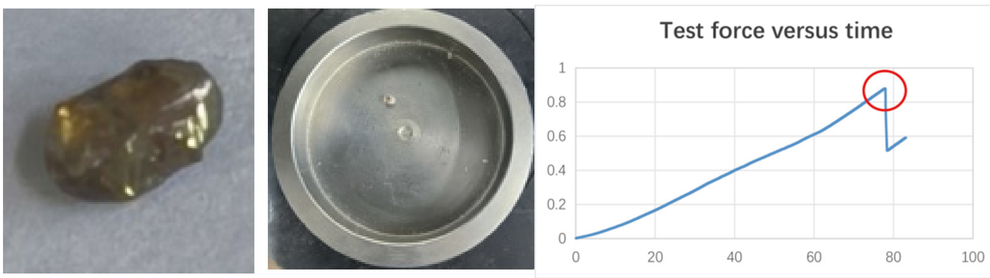

Fig 16. Low-grade diamond. Particle Size: 3.9mm, Peak Test Force: 0.88kN

The experimental results reveal distinct differences in the crushing behavior of diamond particles across high, medium, and low grades. The crush morphology of the diamond particles can be classified into three categories: Complete Crushing, Partial Detachment, and No Significant Crushing, as illustrated in Figure 17.

Complete Crushing (CC) is characterized by the entire particle breaking apart, often accompanied by a loud collision sound from the compression plates. Partial Detachment (PD) involves the localized breaking of the particle, with fragments detaching from the original grain. No Significant Crushing (NSC) occurs when the instrument detects a fracture or breakage, causing it to automatically stop applying pressure, yet no visible changes are observed to the naked eye.

The post-experiment analysis indicates that the crushing behavior varies significantly among the different grades of diamond particles. High-grade diamond particles predominantly exhibit CC. This suggests that high-grade diamonds, while strong, tend to fail catastrophically under high compressive loads.

Medium-grade diamond particles also show instances of CC and PD, but PD is more common. This indicates that medium-grade diamonds have a higher tendency to experience localized failure rather than complete disintegration, reflecting a balance between strength and brittleness.

Low-grade diamond particles display all three types of crushing behavior, with CC and PD being the most prevalent. The presence of all three failure modes in low-grade diamonds suggests a higher variability in their structural integrity and mechanical properties. This variability could be attributed to the presence of more impurities and structural defects in low-grade diamonds, making them less predictable under compressive stress.

(a) (b) (c)

Fig 17. (a) Complete Crushing, (b) Partial Detachment, (c) No Significant Crushing

Table 3 provides a comprehensive summary of the experimental records for the single diamond grain crushing tests. This table consolidates the key findings from the experiments, including the peak forces, particle sizes, and other relevant parameters for each grade of diamond particles. The data presented in Table 3 offer a clear and concise reference for comparing the performance of high-grade, medium-grade, and low-grade diamond particles in terms of their crushing strength.

Figures 18 and 19 illustrate the experimental results through bar charts. Figure 18 presents the maximum load forces recorded during the diamond crushing tests, while Figure 19 shows the average maximum load forces for each grade of diamond particles. These visual representations provide an intuitive understanding of the differences in mechanical properties among the various grades of diamond particles. Overall, the experimental results indicate that higher-grade diamond particles exhibit more stable maximum load forces and higher numerical values of maximum load forces. As the grade of the diamond particles decreases from high to medium to low, the maximum load force that the diamond particles can withstand (i.e., the force required to initiate the first fracture of the diamond) also decreases. This trend can be attributed to the more complete and uniformly distributed crystal structures in high-grade diamonds. When subjected to compressive stress, the stress is evenly dispersed within the crystal, reducing the likelihood of stress concentration and subsequent cracking. In contrast, medium- and low-grade diamonds have less complete crystal structures and more defects, which lead to stress concentration at these defects and result in cracking and crushing.

Additionally, the experimental data reveal that as the particle size of the diamond increases, the average maximum load force decreases. This phenomenon occurs because larger particles tend to have more crystal defects, and the grain boundary effects become more pronounced. These defects and grain boundaries act as stress concentrators, making it easier for cracks to form and propagate, thereby reducing the overall crushing strength of the diamond particles.

In conclusion, the experimental findings highlight the significant influence of diamond grade and particle size on the crushing strength of diamond particles. High-grade diamonds, with their more complete and uniform crystal structures, exhibit higher and more stable maximum load forces. Conversely, medium- and low-grade diamonds, with their greater number of defects, show lower crushing strengths. Furthermore, larger diamond particles tend to have lower average maximum load forces due to the increased presence of defects and grain boundary effects. These insights are crucial for optimizing the use of diamond particles in industrial applications, where precision and durability are essential.

Table 3. Experimental Record of Single Diamond Grain Crushing Test

Label	Grade	Size distribution	Diameter/mm	Peak load/kN	Average strength/kN
1	High	2.8-3.0mm	2.9	1.55	2.19
2	High		2.8	2.14	
3	High		2.8	2.54	
4	High		2.9	2.52	
5	High	3.1-3.3mm	3.2	1.87	2.12
6	High		3.1	2.37	
7	High	3.4-3.6mm	3.6	2.71	1.67
8	High		3.4	0.63	
9	Medium	1.7-2.0mm	2.0	1.12	1.30
10	Medium		1.7	1.82	
11	Medium		2.0	0.83	
12	Medium		2.0	1.42	
13	Medium	2.1-2.4mm	2.2	1.80	1.44
14	Medium		2.3	3.25	
15	Medium		2.2	1.03	
16	Medium		2.2	1.50	
17	Medium	2.5-2.7mm	2.5	0.72	0.66
18	Medium		2.6	0.45	
19	Medium		2.6	0.46	
20	Medium		2.6	1.01	
21	Low	2.5-3.0mm	2.5	1.56	1.70
22	Low		2.6	2.40	
23	Low		2.7	2.42	
24	Low		3.0	0.41	
25	Low	3.1-3.6mm	3.3	0.28	0.34
26	Low		3.6	0.20	
27	Low		3.3	0.54	
28	Low	3.7-4.2mm	3.9	0.88	0.80
29	Low		4.2	1.07	
30	Low		4.0	0.64	
31	Low		3.8	0.63	

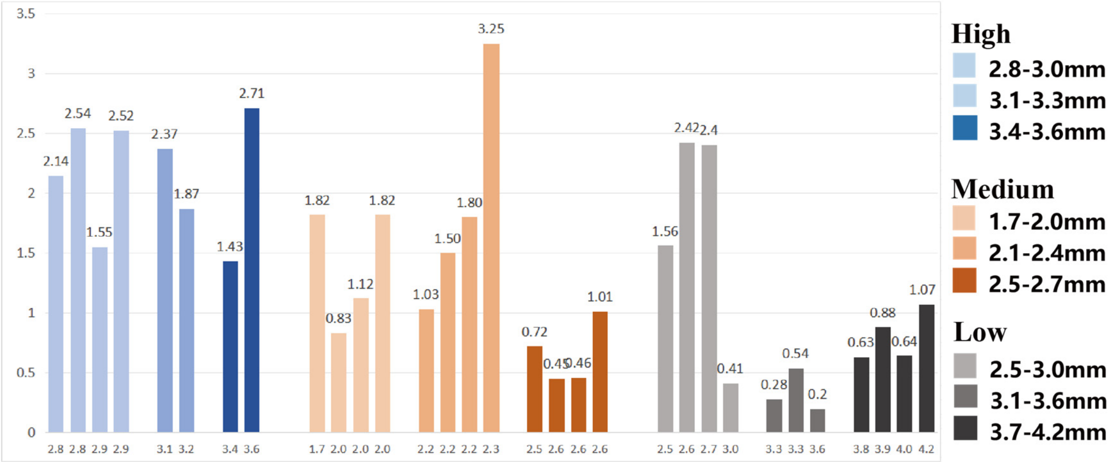

Fig 18. Bar Chart of Maximum Load Forces in Diamond Crushing Test

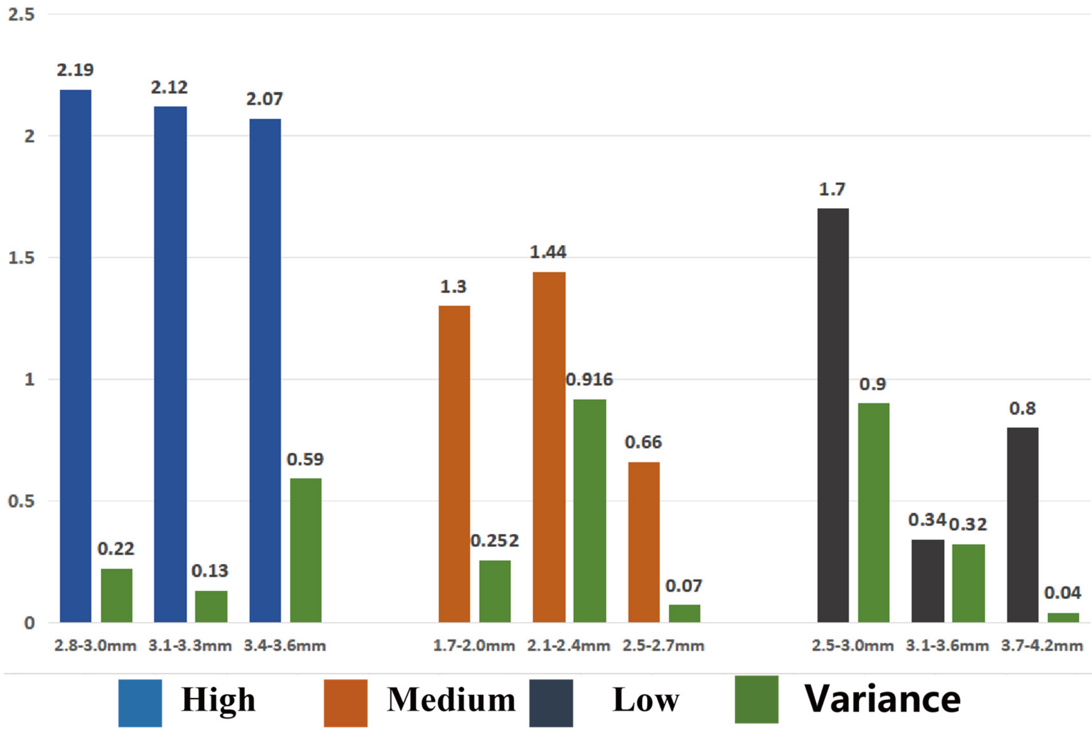

Fig 19. Bar Chart of Average Maximum Load Forces in Diamond Crushing Test

4. CONCLUSION

This work presents the results of static compression experiments conducted on single diamond grains of varying grades and particle sizes using the WDW-100 electronic universal testing machine. The morphological changes and crushing strength of the diamond particles were analyzed, leading to the following key conclusions:

1) Crushing Behavior by Grade: High-grade diamond particles are more prone to complete crushing, characterized by a pulverizing fracture. In contrast, medium- and low-grade diamond particles primarily exhibit partial crushing, where only localized regions of the particles break apart. This indicates that the structural integrity of high-grade diamonds is more susceptible to catastrophic failure under compressive loads, whereas lower-grade diamonds tend to fail in a more localized manner.

2) Maximum Load Capacity by Grade: As the grade of the diamond particles decreases from high to medium to low, the maximum load force that the diamond particles can withstand—defined as the force required to initiate the first fracture—also decreases. This trend suggests that higher-grade diamonds, with their more complete and uniformly distributed crystal structures, can endure greater compressive forces before failing. Conversely, the presence of more defects and less uniform crystal structures in lower-grade diamonds leads to earlier failure under lower compressive forces.

3) Effect of Particle Size on Load Capacity: An increase in the particle size of the diamond grains corresponds to a decrease in the average maximum load force. Larger diamond particles tend to have more crystal defects and pronounced grain boundary effects, which act as stress concentrators. These defects facilitate the initiation and propagation of cracks, thereby reducing the overall crushing strength of the diamond particles. This finding underscores the importance of considering particle size in applications where the mechanical strength of diamond particles is critical.

REFERENCES

[1] Cai M, Li M, Zhu X, et al. Comprehensive Evaluation of Rock Mechanical Properties and in-situ Stress in Tight Sandstone Oil Reservoirs[J]. Frontiers in Earth Science, 2022, 10: 911504.

[2] Huang T, Wang L, Li J, et al. Study on mechanical properties and fracture surface characteristics of argillaceous sandstone under different stress paths[J]. Scientific Reports, Nature Publishing Group, 2022, 12(1): 16072.

[3] Polini W, Turchetta S. Evaluation of diamond tool wear[J]. The International Journal of Advanced Manufacturing Technology, 2005, 26(9–10): 959–964.

[4] Liu H, Zong W, Cui Z. Durability of micro diamond tools with different crystallographic planes[J]. Journal of Materials Processing Technology, 2022, 305: 117600.

[5] Malevich N, Müller C H, Dreier J, et al. Experimental and statistical analysis of the wear of diamond impregnated tools[J]. Wear, 2021, 468–469: 203574.

[6] Li G, Rahim M Z, Pan W, et al. The manufacturing and the application of polycrystalline diamond tools – A comprehensive review[J]. Journal of Manufacturing Processes, 2020, 56: 400–416.

[7] Kansteiner M, Biermann D. Influence of the diamond grain shape and orientation on the process forces and the mechanical work in scratch tests on basalt stone[J]. Diamond and Related Materials, 2019, 94: 65–72.

[8] Bhamra J S, Ewen J P, Latorre C A, et al. Interfacial Bonding Controls Friction in Diamond–Rock Contacts[J]. The Journal of Physical Chemistry C, 2021, 125(33): 18395–18408.

[9] Dubrovinskaia N, Dubrovinsky L, Solopova N A, et al. Terapascal static pressure generation with ultrahigh yield strength nanodiamond[J]. Science Advances, 2016, 2(7): e1600341.

[10] Strength and fracture properties of diamond: Philosophical Magazine A: Vol 43, No 3[EB/OL]. [2024-10-09]. https://www.tandfonline.com/doi/abs/10.1080/01418618108240397.

[11] Lou B, Li P, Li L. Failure Analysis and Strengthening Method for Circular Diamond Saw Blade[C]//Jiang Z Y, Han J T, Liu X H. NEW MATERIALS AND ADVANCED MATERIALS, PTS 1 AND 2. Stafa-Zurich: Trans Tech Publications Ltd, 2011, 152–153: 1616–1619.

[12] Chen J, Liu W, Wang B. Prediction of theoretical strength of diamond under complex loadings[J]. Extreme Mechanics Letters, 2021, 44: 101233.

[13] Sumiya H, Sakano F, Tatsumi N. Distribution of internal strain and fracture strength in various single-crystal diamonds[J]. Diamond and Related Materials, 2023, 134: 109781.

[14] Zhang G, Zhao S, Qin H, et al. A unified strength criterion of diamane grain boundaries[J]. Extreme Mechanics Letters, 2024, 68: 102146.

[15] Field J E. The mechanical and strength properties of diamond[J]. Reports on Progress in Physics, IOP Publishing, 2012, 75(12): 126505.

[16] Ikeda R, Hayashi M, Yonezu A, et al. Fracture observation of polycrystalline diamond film under indentation test[J]. Diamond and Related Materials, 2004, 13(11): 2024–2030.

[17] Brenner D W, Shenderova O A. Theory and modelling of diamond fracture from an atomic perspective [J]. PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A-MATHEMATICAL PHYSICAL AND ENGINEERING SCIENCES, London: Royal Soc, 2015, 373(2038): UNSP 20140139.

[18] Lang J M, Winey J M, Gupta Y M. Strength and deformation of shocked diamond single crystals: Orientation dependence[J]. Physical Review B, American Physical Society, 2018, 97(10): 104106.

[19] Guan S, Peng F, Liang H, et al. Fragmentation and stress diversification in diamond powder under high pressure[J]. Journal of Applied Physics, 2018, 124(21): 215902.

[20] Field J E, Freeman C J. Strength and fracture properties of diamond[J]. Philosophical Magazine A, Taylor & Francis, 1981, 43(3): 595–618.