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ORIGINAL ARTICLE

A multi-phase micro-abrasive jet machining technique for the surface texturing of mechanical seals

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Abstract The surface texture such as micro-dimples or micro-grooves on the surface of mechanical seals can help to improve the tribological and sealing properties. A technique of multi-phase micro-abrasive jet machining is proposed to fabricate micro-grooves on the surface of mechanical seals. This technique takes the advantages of the current micro-abrasive jet machining and can recycle the abrasive particles easily to avoid the pollution on the environments by accelerating the mixture of abrasives and water with compressed air. The machining effects on three typical materials for mechanical seals are investigated and compared. The influences of machining times, abrasive flow rate, jet pressure, and jet distance on machining quality are studied and optimized through experiments.

Keywords Multi-phase micro-abrasive jet machining · Surface texture · Micro-grooves · Mechanical seals

1 Introduction

Mechanical seals are widely used in hydraulic systems, transmissions, and aero-engines to avoid the leakage of fluids by mutual mating the faces of rotating and stationary rings. The wear on the mating surfaces could lead to serious problems which limits the performances, stability, durability, and reliability of mechanical seals, particularly, while the PV value, the product of contact pressure and linear velocity is increased dramatically in modern machines [1].

Surface texture has been proven as an effective means to improve the tribological and sealing properties of mechanical seals [2–4]. By fabricating various patterns of grooves or dimples in macro- or micro-scale on the mating surfaces, additional hydrodynamic pressure could be generated to increase the load carrying capacity and the fluid film stiffness between the rotating and stationary rings [5–8]. Usually, the dimensions of the grooves or dimples vary in the range from 50 μm to millimeters in diameter or length/width and 5~20 μm in depth [9–11].

Many machining techniques have been developed for the fabrication of micro-dimples or grooves on different materials. Micro-cutting or milling is a cheap and convenient machining method for relative soft materials, but usually it would generate bulges or burrs, and be hard to satisfy the demand of micro-scale precision on hard and brittle materials [12, 13]. Electrochemical machining is proved to be capable of large-scale industrial production since its process is simple and many structures can be processed at the same time, but it can only be applied for electrical conductive materials [14]. Micro-ultrasonic machining removes materials by the impact of abrasive grains to which kinetic energy is given by an acoustic system. It is effective for the machining on hard and fragile materials such as glass, silicon, and ceramic, although often associated with the adverse effect of tool wear on machining precision [15]. The laser machining is one of the most widely used methods for a wide range of materials, but the surface may have heat-affected regions, bulges or burrs around the structure, which require post-processing steps to be removed [16–18].

Sand blasting is a traditional process in which a stream of sand is being propelled against a surface to remove contaminants, to smooth a rough surface, or to roughen a smooth surface. Belloy et al. [19] proposed the micro-abrasive jet

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machining (MAJM) which adopts small abrasive particles such as alumina around 30 μm instead of sand for the fabrication of micro-systems. Good machining performances were achieved when Wakuda et al. [20–22] applied MAJM to fabricate micro-dimples or micro-grooves on silicon nitride, optical glass, and stainless steel. Similar researches also indicate that the MAJM technique is suitable for a wide range of materials, with no heat-affected zone, and a small counterforce [23–25].

In the process of MAJM, abrasive particles are accelerated by compressed air and the material is removed by the impact and polishing-grinding of abrasives. Large particles may achieve high machining efficiency as well as small particles get good surface quality and high precision, so the size of abrasive particles used in MAJM is usually ranging from 5 to 30 μm to obtain both relatively high machining efficiency and high quality of micro-structures. It is interesting that Wakuda et al. [26] found that the strength of MAJM-finished surfaces of several common ceramics is increased under the impact of small abrasives comparing with that by large particles.

However, in MAJM process, the abrasive particles in small size cannot be recycled easily and have the risk to pollute the environment, and it is expensive to utilize the abrasives with high hardness like synthetic diamond [24]. In 2008, Tsai et al. [27] mixed abrasives with water and a specific quantity of machining oil in the air jet process to polish the die surfaces made of steel. Small size of abrasives (1.6 μm in diameter), large nozzle (4 mm in diameter), and 30° jet angle were used to improve the quality and efficiency of polishing over a relative large area. This idea provides a reference for solving the problems including abrasive recycling and environmental pollution of MAJM process.

Therefore, a technique of multi-phase micro-abrasive jet machining is proposed in this paper for the surface texturing on mechanical seals. Abrasive particles and water are first mixed at a certain ratio with dispersing agent; then, the mixture is inhaled into the nozzle, formed as high-speed multi-phase jetting flow by compressed air, and finally jetted to the surface of mechanical seals. Three typical materials of mechanical seals, i.e., reaction-bonded silicon carbide (RBSC), 304 stainless steel, and carbon graphite, are selected for machining tests. The influence of machining times, abrasive flow rate, jet pressure, and jet distance on the groove depth and surface roughness is studied to evaluate the efficiency and quality of multi-phase micro-abrasive jet machining.

2 Experimental design

2.1 Experimental system design

A multi-phase micro-abrasive jet machining system has been developed as shown in Fig. 1 The air compressor provides compressed air with the pressure up to 0.8 MPa through air filter, pressure-reducing valve, throttle, and ball valve in sequence to the nozzle. For the purpose of micro-machining, the particles of green silicon carbide with the average diameter of 15 μm were used as the abrasives. The abrasives were added in water with a mixing ratio of 1: 10. The mixture of abrasives and water is inhaled, accelerated and formed as high-speed multi-phase jetting flow through the inner venturi tube in the nozzle by compressed air, and finally jetted to the surface of workpiece. A relative small nozzle (1.3 mm in diameter) and 90° jetting angle were adopted to satisfy the requirements of machining of small features. Because of the existence of water, the abrasives could be gathered into the storage tank and recycled easily. The *XY*- and *Z*-axis stages are driven by servo motors controlled by a computer, so that the horizontal motions of the workpiece and the jet distance can be controlled precisely.

In the traditional air jet and water jet devices, the nozzle transforms compressed fluid into jetting flow. While considering air or water as an ideal fluid and ignoring the existence of abrasive particles, the flow of air or water throughout the system follows the principle of conservation of energy and could be expressed by the Bernoulli's equation as

$$p + \rho g h = \frac{\rho v^2}{2}, \tag{1}$$

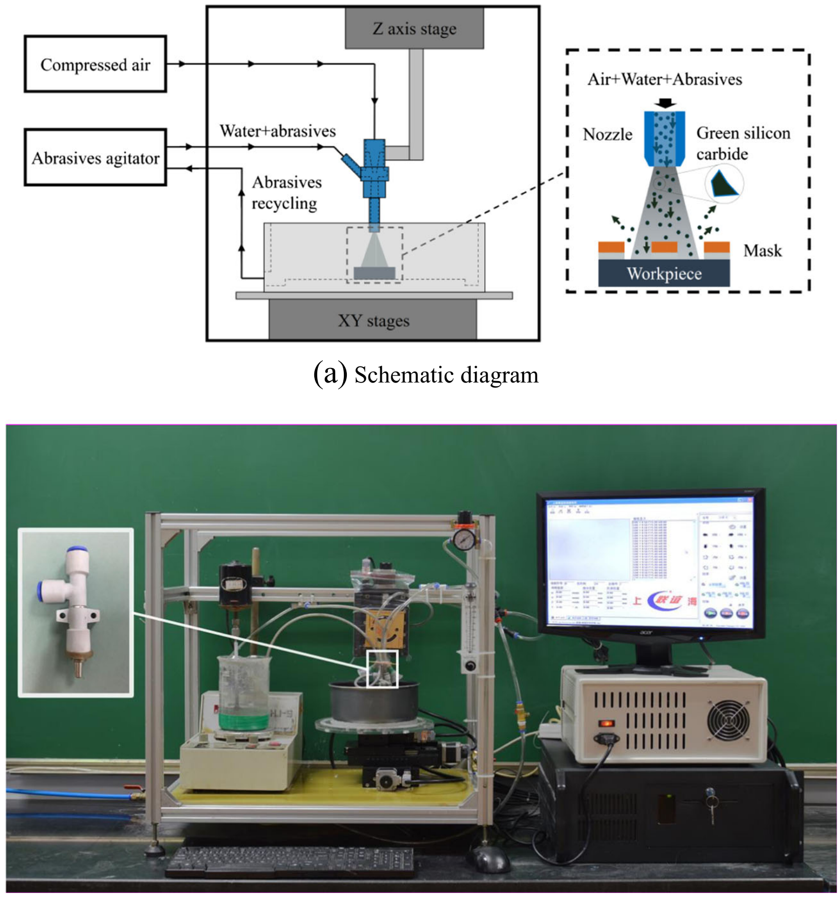
where p represents the pressure of the compressed fluid, ρ is the density of the fluid, g is the gravitational acceleration, h is the changes in elevation, and v is the fluid flow speed. The term ρgh can be omitted since it is at least four orders of magnitude smaller than the other terms, so that the Eq. (1) can be simplified as:

$$v = \sqrt{\frac{2p}{\rho}} \tag{2}$$

Hence, theoretically, when the absolute pressure of the compressed air is 0.174 MPa, the flow speed of air jetting could achieve the speed of sound (C=340 m/s), which only could be realized by the pressure as high as 57.8 MPa in the case of water jetting. Consequently, besides solving the problems of abrasives recycle and environmental pollution by mixing abrasives with water, the multi-phase micro-abrasive jet machining would take the advantages of air jetting, which accelerate abrasive particles to achieve relative high flow speed with low pressure. And additionally, cooling, lubricating, and buffering effects of water may be potentially helpful to improve the machining quality.

2.2 Machining materials

There are various materials for mechanical seals according to its specific usage [28]. In this paper, three typical materials for



(a) Schematic diagram

(b) Experimental set-up

Fig. 1 The multi-phase micro-abrasive jet machining system. **a** Schematic diagram. **b** Experimental set-up

mechanical seals are selected for machining tests. Among these materials, reaction-bonded silicon carbide (RBSC), a typical hard and brittle material, is good in wear and erosion resistance; SUS304, a chrome-nickel stainless steel, is extensively used in mechanical elements for its good resistance in erosion, high thermal conductivity, and good machining properties; carbon graphite is a kind of soft material widely used for mechanical seals for its good performance in self-lubricity and chemical inertness. The main properties of these three materials are listed in Table 1.

2.3 Masking process

In order to fabricate the micro-structures with specific shapes and sizes at desired position, a mask with certain thickness and abrasive resistance is needed in the machining process. In this research, a copper foil tape (1181, 3M, USA) and a dry film (GPM220, DuPont, USA) were utilized to fabricate the mask. The copper foil tape consists of two layers, i.e., a layer of copper foil of 40 μm in thickness and a layer of acrylic acid adhesive of 26 μm in thickness. The masking process by through mask electrochemical micro-machining is illustrated in Fig. 2

(1) Adhering: The copper foil tape was first adhered to the workpiece at ambient temperature, then, the dry film was rolled and heated to attach on the copper foil tape.
(2) Exposing: The dry film was covered by the lithography mask with specific pattern of surface texture and then exposed under ultraviolet radiation by the exposure

Table 1 Material properties

Materials	Density ρ, g/cm^3	Hardness	Modulus of elasticity E, GPa	Tensile strength σ_b, MPa
RBSC	3.05	HRA 91	330	352
SUS304	7.93	HRB 89	193	535
Carbon graphite	1.82	HS 55	28	55

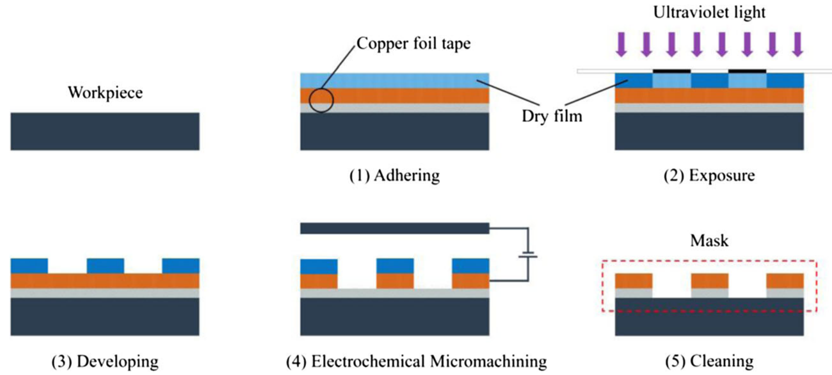


Fig. 2 Masking process before machining

machine (BG-401, China). The optical power density of the exposure mercury lamp was 70 mW/cm^2 and the exposure lasted for 1 s.

(3) Developing: The exposed dry film was put into the 1 % Na_2CO_3 solution and developed for 90 s with gentle shaking, then, rinsed by distilled water. After above steps, the pattern on the lithography mask was transferred to the dry film.

(4) Electrochemical machining: The pattern on the dry film was transferred to the copper foil by electrochemical etching process [14].

(5) Cleaning: The specimen was put into acetone for ultrasonic cleaning for 90 s to remove the dry film on the surface. After that, the specimen is ready for the abrasive jet machining.

Figure 3 shows a prepared mask, which has a thickness of 55 ± 5 μm, and the groove width of 310 ± 10 μm measured by an optical 3D profiler.

2.4 Machining details

In order to obtain a uniform machining depth, S-type relative motion between the nozzle and workpiece was realized by the *XY* stages as shown in Fig. 4. The final machined surface is actually the accumulated results of the machining in S-type motion. The effects of machining times, i.e., the times the nozzle passes over the same region, are of great guiding significance in designing the feeding mode and machining parameters to achieve desired depth and surface quality of the micro-grooves [29]. Similar researches on micro-abrasive jet machining also indicate that abrasive flow rate, jet pressure, and jet distance are important factors in determining machining effects [19, 26].

In this paper, three materials are tested to investigate the influence of machining times, abrasive flow rate, jet pressure, and jet distance on the machining effects. The applied parameters of the machining process are shown in Table 2. The machining results were observed by a digital microscope (KEYENCE, Japan). The depth of micro-grooves and the surface roughness at the bottom of grooves (sampling area 250 ± 25 μm^2, rectangle) were measured by an optical 3D profiler (Rtec Instrument, USA).

3 Results and discussion

3.1 The machining effects on different materials

In order to study the effects of the multi-phase micro-abrasive jet machining on different materials, the micro-grooves with the same width were machined on RBSC, SUS304, and

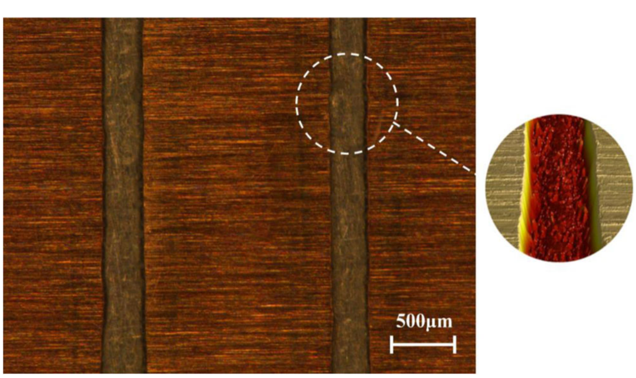


Fig. 3 Appearance of a mask

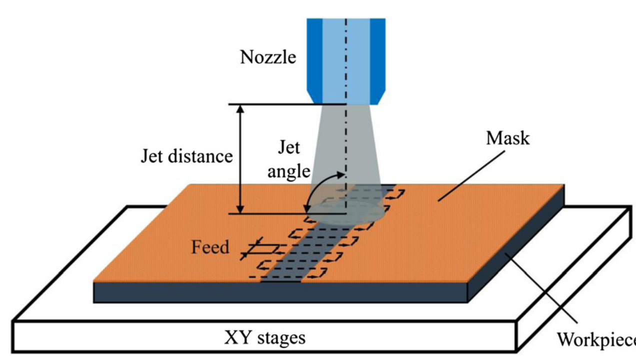


Fig. 4 Schematic diagram of the feeding mode

Table 2 The parameters for the multi-phase micro-abrasive jet machining

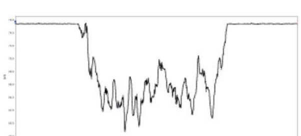
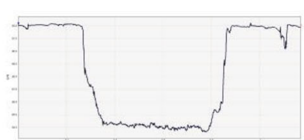
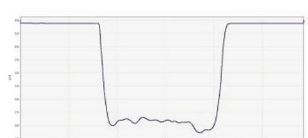
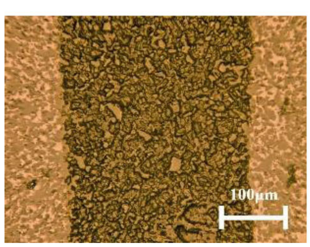
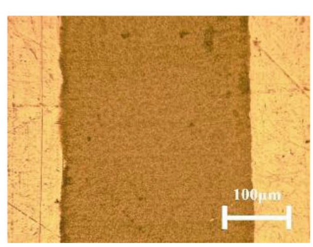
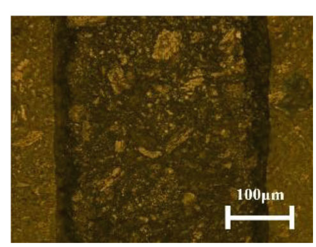
Nozzle shape	Round
Nozzle diameter	1.3 mm
Jet angle	90°
Feed	50 μm
Nozzle moving rate	0.5 mm/s
Abrasive particles	Green silicon carbide, GC#800
Particle mean diameter	15 μm
Abrasive flow rate	3–27 g/min
Jet pressure	0.2–0.6 MPa
Jet distance	1–15 mm

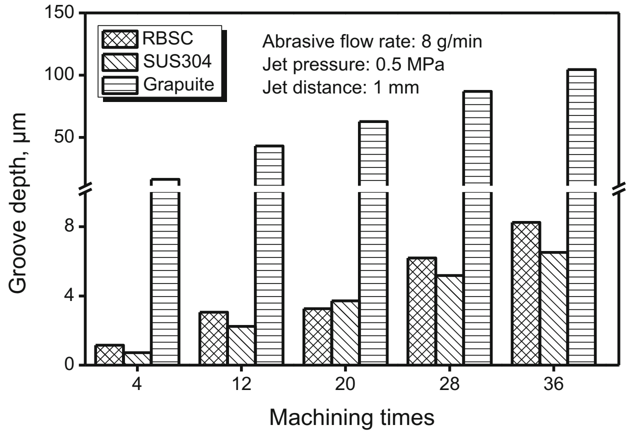
carbon graphite, respectively, with abrasive flow rate 8 g/min, jet pressure 0.6 MPa, and jet distance 9 mm with S-type feed mode. The machining effects are shown in Table 3. It can be found that the mask used in this paper achieved good locality and that micro-groove width was effectively controlled. Among these three materials, SUS304 has moderate hardness and high tensile strength; plastic deformation might appear on the surface when abrasives impacting and shearing are involved in the machining process, so that lower surface roughness on the groove bottom was achieved. Meanwhile, the machining efficiency on RBSC was slightly higher than that of SUS304, but it was hard to control the surface quality of RBSC for its high hardness and low tenacity, so the surface roughness inside the micro-groove was higher than that of SUS304. Under the same machining conditions, the machining efficiency for carbon graphite was much higher than that for RBSC and SUS304, but the surface roughness was also higher than the other two materials.

3.2 The effect of machining times

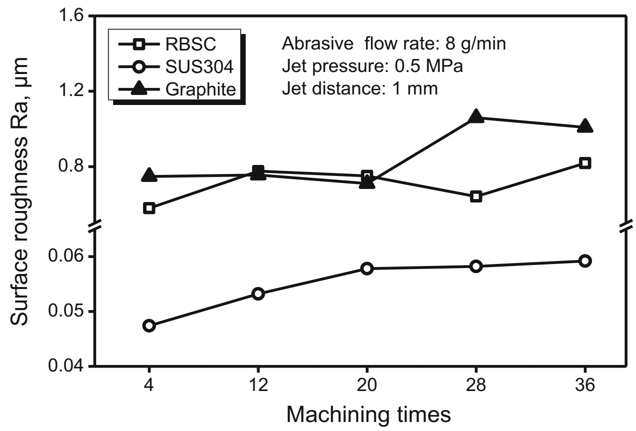
Under the same jetting conditions, the machining depth would depend on the machining times, which is defined as the times of the nozzle passing over the same area. With abrasive flow rate 8 g/min, jet pressure 0.5 MPa, jet distance 1 mm, and feeding speed of 0.5 mm/s, the effects of machining times on micro-groove depth and surface roughness on the bottom of micro-grooves are shown in Fig. 5. It is found that micro-groove depth increased progressively in arithmetic sequence with the increase of machining times within a certain range. It indicates that the multi-phase micro-abrasive jet machining technique has a stable material removal rate in machining, and machining depth can get well controlled. Meanwhile, surface roughness of the micro-groove bottom increased gradually at the beginning and then towards a stable value as machining times and groove depth increased.

Table 3 The properties of micro-grooves fabricated on different materials

Materials	RBSC	SUS304	Carbon graphite
Micro-groove depth *h*, μm	9.444	7.834	178.5
Surface roughness Ra, μm	0.670	0.047	0.934
Cross-sectional shape			
Microscope image			

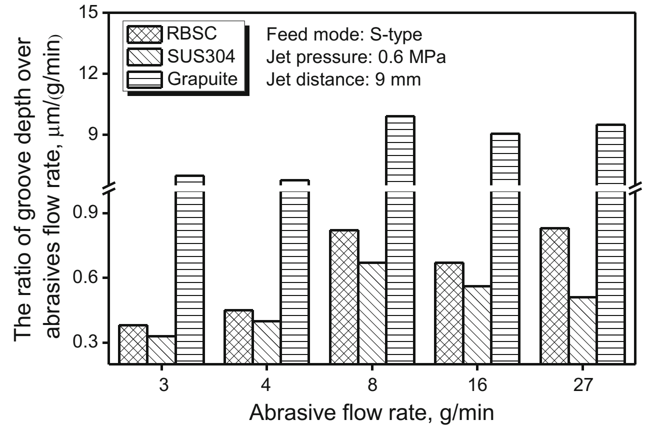


(a) Groove depth

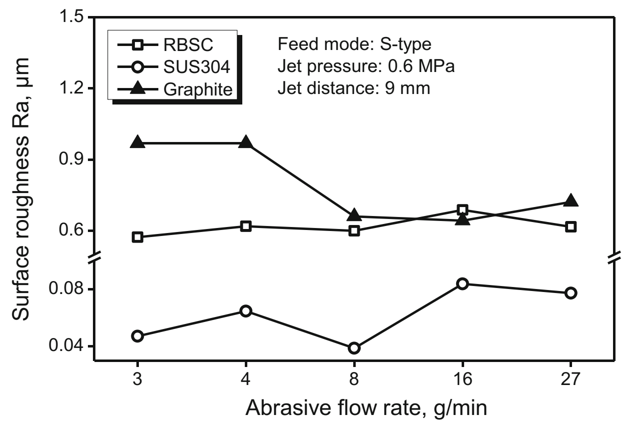


(b) Surface roughness

Fig. 5 The effects of machining times on **a** groove depth and **b** surface roughness



(a) The ratio of groove depth over abrasive flow rate



(b) Surface roughness

Fig. 6 The effects of abrasive flow rate. **a** The ratio of groove depth over abrasive flow rate. **b** Surface roughness

3.3 The effects of abrasive flow rate

Figure 6 shows the effects of abrasive flow rate on the groove depth and surface roughness inside the grooves with jet pressure of 0.6 MPa and jet distance of 9 mm. The ratio of groove depth over abrasive flow rate is used as an index to evaluate the machining efficiency of abrasives. It can be found the ratio of groove depth over abrasive flow rate has relative high values when abrasive flow rate is 8 g/min, indicating that abrasives have high machining efficiency at this condition. Fortunately, a relative low surface roughness on the groove bottom was also obtained. Of course, low content of abrasives would not be capable of effective machining. However, the experimental results also indicate that the efficiency of abrasives decreased when abrasive flow rate is increased after 8 g/min. The reason could be that the abrasives may bounce on the surface and collide to each other in the jetting flow, which decreases the kinetic energy of abrasives, resulting in low utilization of abrasives and high surface roughness. The higher the abrasive flow rate is, the more obvious the effect is. Hence, proper abrasive flow rate should be chosen in the machining process.

3.4 The effects of jet pressure

The experiments on the effects of jet pressure were carried out under the conditions that abrasive flow rate was 8 g/min and jet distance was 9 mm with S-type feed mode. As shown in Fig. 7, the machining efficiency on the three materials increases while the jet pressure is increased, but not proportional to the jet pressure. The abrasive particles would have more kinetic energy while the jet pressure is high. Obviously, a low jet pressure would not ensure enough energy to realize effective or highly efficient machining on hard materials. Increasing the jet pressure will increase the kinetic energy which results in an increase in material removal rate. However, an excessive high material removal rate makes it difficult to control the depth of micro-groove precisely, and the surface roughness also increases when jet pressure is high. Therefore, proper jet pressure should be chosen according to different properties of materials.

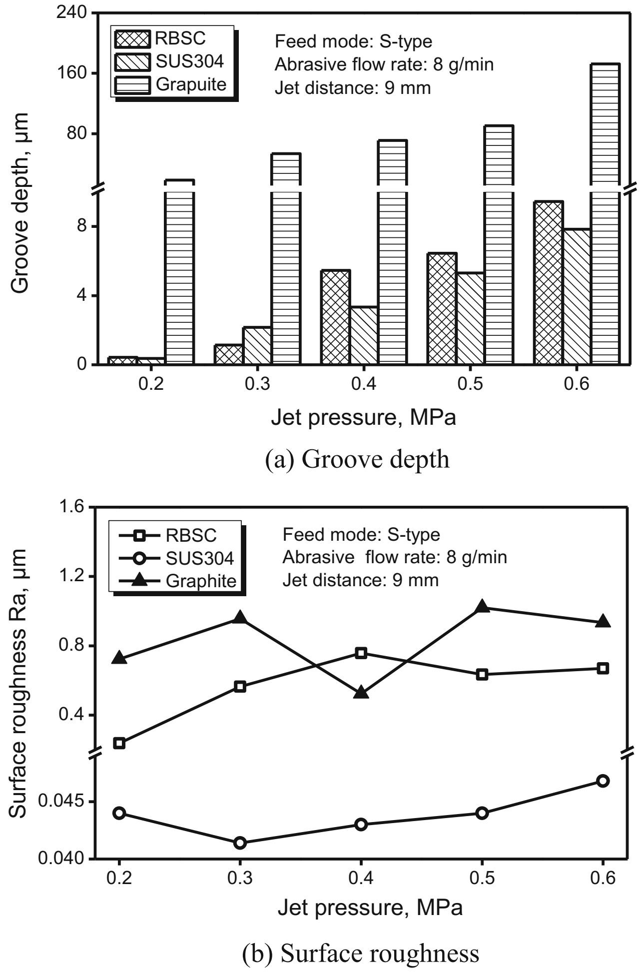


Fig. 7 The effects of jet pressure on **a** groove depth and **b** surface roughness

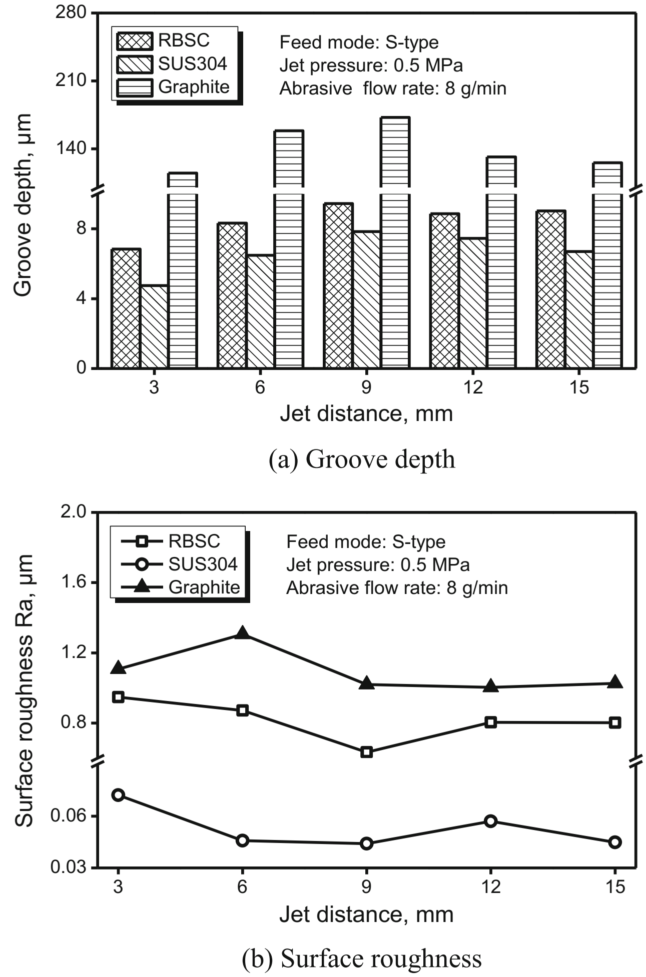


Fig. 8 The effects of jet distance on **a** groove depth and **b** surface roughness

3.5 The effects of jet distance

At the abrasive flow rate of 8 g/min, jet pressure of 0.5 MPa, and S-type feed mode, the effects of jet distance on the depth and surface roughness of micro-grooves were investigated. As shown in Fig. 8, it is found that both too short and too long jet distance would decrease the machining efficiency and the surface quality, indicating there is an optimal jet distance around 9 mm, at which high machining efficiency and low surface roughness could be achieved for these three materials. This result can be interpreted as the effect of bounce flow. The jetting flow is more concentrated while it just gets out of the nozzle and then diverges gradually along the increase of jet distance. Within a short jet distance, there would be more bounce flow after the jet flow strikes the surface of workpiece, which decreases the kinetic energy of the following jet flow. On the other hand, the jet flow diverges too much and the jet speed decreases if the jet distance is too long. Therefore, proper jet distance should be used to obtain desired machining performance.

4 Conclusions

A technique of multi-phase micro-abrasive jet machining is proposed for the surface texturing of mechanical seals. A series of experiments were performed and present results support the following conclusions:

(1) The multi-phase micro-abrasive jet machining takes the advantages of air jet machining to form a high-speed flow with a relative low pressure of air, and solves the problems of abrasive recycle and environmental pollution.
(2) The multi-phase micro-abrasive jet machining could be used for the surface texturing for the typical materials such as RBSC, SUS304, and carbon graphite for mechanical seals. The machining efficiency and surface quality depend on the material properties. Carbon graphite has high material removal rate, and SUS304 could have low surface roughness after machining.

(3) The optimal values of jet distance and abrasive flow rate are obtained in this paper, and desirable machining effects can be achieved by adjusting the machining times and jet pressure.

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References

1. Nau BS (1990) Research in mechanical seals. Proc Inst Mech Eng C J Mech Eng Sci 204(6):349–376
2. Etsion I, Halperin G (2002) A laser surface textured hydrostatic mechanical seal. Tribol Trans 45(3):430–434
3. Wang X, Kato K, Adachi K (2002) The lubrication effect of micro-pits on parallel sliding faces of SiC in water. Tribol Trans 45(3): 294–301
4. Meng X, Bai S, Peng X (2014) Lubrication film flow control by oriented dimples for liquid lubricated mechanical seals. Tribol Int 77:132–141
5. Brunetière N, Tournerie B (2012) Numerical analysis of a surface-textured mechanical seal operating in mixed lubrication regime. Tribol Int 49:80–89
6. Wang X, Kato K, Adachi K, Aizawa K (2003) Loads carrying capacity map for the surface texture design of SiC thrust bearing sliding in water. Tribol Int 36(3):189–197
7. Bai S, Peng X, Li Y, Sheng S (2010) A hydrodynamic laser surface-textured gas mechanical face seal. Tribol Lett 38(2):187–194
8. Yuan S, Huang W, Wang X (2011) Orientation effects of micro-grooves on sliding surfaces. Tribol Int 44(9):1047–1054
9. Yu H, Huang W, Wang X (2013) Dimple patterns design for different circumstances. Lubr Sci 25(2):67–78
10. Wang X, Adachi K, Otsuka K, Kato K (2006) Optimization of the surface texture for silicon carbide sliding in water. Appl Surf Sci 253(3):1282–1286
11. Shi L, Wang X, Su X, Huang W, Wang X (2015) Comparison of the performances of mechanical gas seals textured with micro-grooves and micro-dimples. J Tribol 138(2):021701
12. Chae J, Park SS, Freiheit T (2006) Investigation of micro-cutting operations. Int J Mach Tools Manuf 46(3):313–332
13. Zhang T, Liu Z, Xu C (2013) Influence of size effect on burr formation in micro cutting. Int J Adv Manuf Technol 68(9–12):1911–1917
14. Qian S, Zhu D, Qu N, Li H, Yan D (2009) Generating micro-dimples array on the hard chrome-coated surface by modified through mask electrochemical micromachining. Int J Adv Manuf Technol 47(9–12):1121–1127
15. Yu ZY, Rajurkar KP, Tandon A (2004) Study of 3D micro-ultrasonic machining. J Manuf Sci Eng 126(4):727–732
16. Etsion I (2005) State of the art in laser surface texturing. J Tribol 127(1):248–253
17. Coblas DG, Fatu A, Maoui A, Hajjam M (2015) Manufacturing textured surfaces: state of art and recent developments. Proc Inst Mech Eng, Part J: J Eng Tribol 229(1):3–29
18. Huynh VM, Fan Y (1992) Surface-texture measurement and characterisation with applications to machine-tool monitoring. Int J Adv Manuf Technol 7(1):2–10
19. Belloy E, Thurre S, Walckiers E, Sayah A, Gijs M (2000) The introduction of powder blasting for sensor and microsystem applications. Sensors Actuators A Phys 84(3):330–337
20. Wakuda M, Yamauchi Y, Kanzaki S (2003) Material response to particle impact during abrasive jet machining of alumina ceramics. J Mater Process Technol 132(1):177–183
21. Park DS, Cho MW, Lee H, Cho W (2004) Micro-grooving of glass using micro-abrasive jet machining. J Mater Process Technol 146(2):234–240
22. Nakano M, Korenaga A, Korenaga A, Miyake K, Murakami T, Ando Y, Usami H, Sasaki S (2007) Applying micro-texture to cast iron surfaces to reduce the friction coefficient under lubricated conditions. Tribol Lett 28(2):131–137
23. Balasubramaniam R, Krishnan J, Ramakrishnan N (2002) A study on the shape of the surface generated by abrasive jet machining. J Mater Process Technol 121(1):102–106
24. Getu H, Ghobeity A, Spelt JK, Papini M (2008) Abrasive jet micromachining of acrylic and polycarbonate polymers at oblique angles of attack. Wear 265(5):888–901
25. Saragih AS, Ko TJ (2009) Fabrication of passive glass micromixer with third-dimensional feature by employing SU8 mask on micro-abrasive jet machining. Int J Adv Manuf Technol 42(5–6):474–481
26. Wakuda M, Yamauchi Y, Kanzaki S (2002) Effect of workpiece properties on machinability in abrasive jet machining of ceramic materials. Precis Eng 26(2):193–198
27. Tsai FC, Yan BH, Kuan CY, Huang FY (2008) A Taguchi and experimental investigation into the optimal processing conditions for the abrasive jet polishing of SKD61 mold steel. Int J Mach Tools Manuf 48(7):932–945
28. Nau BS (1997) Mechanical seal face materials. Proc Inst Mech Eng, Part J: J Eng Tribol 211(3):165–183
29. Yagyu H, Hayashi S, Tabata O (2004) Application of nanoparticles dispersed polymer to micropowder blasting mask. J Microelectromech Syst 13(1):1–6