Wang and Wang
Chinese Journal of Mechanical Engineering (2023) 36:132
https://doi.org/10.1186/s10033-023-00948-9

Chinese Journal of Mechanical Engineering

ORIGINAL ARTICLE

Open Access

Effect of Micro Abrasive Slurry Jet Polishing on Properties of Coated Cemented Carbide Tools

Rongjuan Wang[1] and Chengyong Wang[2*]

Abstract

Owing to the popularization of coating technology, physical Vapor Deposition (PVD) coated tools have become indispensable in the cutting process. Additionally, the post-treatment of coated tools applied to industrial production can effectively enhance the surface quality of coating. To improve the processing performance of coated tools, micro abrasive slurry jet (MASJ) polishing technology is first applied to the post-treatment of coated tools. Subsequently, the effects of process parameters on the surface quality and cutting thickness of coating are investigated via single-factor experiments. In the experiment, the best surface roughness is obtained by setting the working pressure to 0.4 MPa, particle size to 3 μm, incidence angle to 30°, and abrasive mass concentration to 100 g/L. Based on the results of the single-factor experiments, combination experiments are designed, and three types of coated tools with different surface qualities and coating thicknesses are obtained. The MASJ process for the post-treatment of coated tools is investigated based on a tool wear experiment and the effects of cutting parameters on the cutting force and workpiece surface quality of three types of cutting tools. The result indicates that MASJ machining can effectively improve the machining performance of coated tools.

Keywords Micro abrasive slurry jet, Post-treatment, Coated tools, Turning, Surface roughness

1 Introduction

Owing to the rapid development of coating technology in recent years, coated tools have been used as the primary cutting tool for material removal [1]. Meanwhile, high-speed cutting, dry cutting conditions, and difficult-to-cut materials impose higher requirements not only on the coating, but also on the coating surface finish and the surface finish of the workpiece. Hence, the post-treatment of coated tools has received significant attention.

The post-treatment of coated tool improves the comprehensive performance of the coating after the tool is coated. Coated tools can be post-treated via one of three methods: micro-blasting [2], heat treatment [3, 4] and laser treatment [5]. Furthermore, micro-blasting has been regarded as an effective method in recent years [6, 7].

The wear resistance [8–11], strength properties [12], formation [13], corrosion resistance [14], and fracture resistance [15] of a coated tool can be improved by micro-blasting it, which can effectively prolong its service life [16]. Jacoba et al. [17] discovered that micro-blasting after deposition can increase the coating hardness, and that post-treated AlTiN-coated tools can significantly reduce cutting forces by up to 27%. Bouzakis et al. [18] reported that wear mechanisms during micro-blasting may reduce the coating thickness and reveal the substrate; hence, the micro-blasting parameters, in particular the pressure and time, must be optimized synthetically. Bouzakis et al. [19] reported that although

*Correspondence:
Chengyong Wang
cywang@gdut.edu.cn
[1] Airport College, Binzhou University, Binzhou 256600, China
[2] School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou 510006, China

increasing the micro-blasting pressure is beneficial for enhancing the properties of coatings, it may increase the film brittleness and result in localized substrate exposure, particularly when ZrO_2 grains are applied at pressures exceeding 0.4 MPa. The effects of sharp-edged Al_2O_3 and smooth spherical ZrO_2 micro-blasting grains on coating mechanical properties, brittleness, tool wedge geometry, and cutting performance were investigated [20]. Bouzakis et al. [21] reported the effect of wet and dry micro-blasting on the hardness, tool wedge geometry, and cutting performance of PVD films with various diameters of Al_2O_3 abrasive grains. The effect of sandblasting on the tribological properties of TiN/MT–iCN/Al_2O_3/TiCNO coating was investigated. It was discovered that micro-sandblasting was critical in improving the wear resistance of coating [22]. Faksa et al. [23] reported that low impact angles, such as 45°, did not shift the initial tensile stresses of TiCN into a compressive state.

The abovementioned studies indicate that the parameter settings for micro-blasting significantly affect the characteristics of coatings to be produced, thus affecting their machining performance. Notably, studies regarding the milling of coated tools are abundant, whereas those regarding turning are few. Additionally, the life time of coated tools was primarily investigated, whereas the cutting force, surface finish and wear mechanism of the coated tool, and surface quality of the workpiece are seldom investigated.

Micro abrasive slurry jet (MASJ) technology is a new technology based on the micro abrasive water jet (MAWJ) process. It offers the advantages of MAWJ technology, including cold processing, no contact, environmental protection, and ease of control [24], but is more concentrated, uniformed, and stabilized than MAWJ technology [25]. MASJ technology can control the surface quality and machining precision of workpieces by controlling the working pressure, incidence angle, and abrasive mass concentration. Hence, MASJ polishing technology is applied to the post-treatment of coated tools to improve their cutting performance. In this study, the effects of the parameters used in an MASJ on the surface quality and removed thickness of a coating were investigated via single-factor experiments. Based on the results obtained, combination experiments were designed, and three types of coated tools with different surface qualities and coating thicknesses were obtained. Subsequently, the post-treatment of coated tools was investigated.

2 Experiment

2.1 Single-Factor Experimental Design of MASJ

The principle of the MASJ processing equipment is shown in Figure 1 (for specific details, please refer to Ref. [25]). To perform MASJ polish on coated tools, the appropriate process parameters must be used. Otherwise, the surface of the cutting tool will thin out, and the substrate will be exposed. Because the cutting temperature and cutting force will increase, the surface quality of the workpiece will deteriorate, and the tool life will shorten significantly. Prior to performing the polishing experiment on a KC5510 coated tool, we selected the appropriate process parameters and designed reasonable single-factor and combination experiments for the MASJ polishing of KC5510, based on the results of glass and die steel from our study. The machining parameters such as the incidence angle, working pressure, particle size, and abrasive mass concentration were selected to conduct the single-factor experiments, as shown in Table 1.

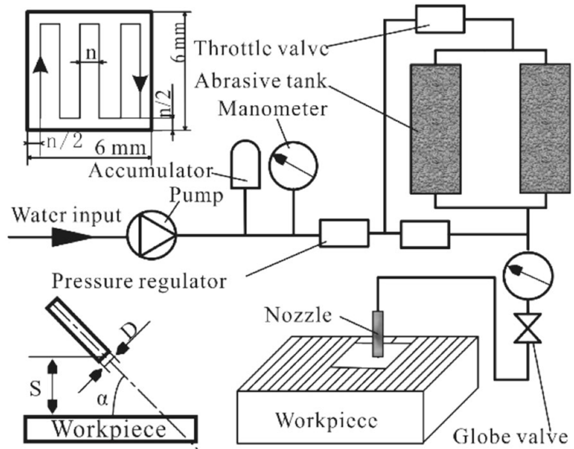

Figure 1 Principle of MASJ process

2.2 Combination Experiment

We designed a combination experiment based on a single-factor experiment. Finally, three types of coated tools with different surface qualities were obtained. These tools were used in subsequent turning experiments. Based on the treatment process of MASJs, an incidence angle of 30°, an working pressure of 0.3 MPa, a particle size of 1 μm, and an abrasive mass concentration of 75 g/L were selected as the polishing process parameters of the KC5510 coated tool, and this set of parameters is termed "one polishing." Additionally, we introduce the term "second polishing," which refers to the parameters of "one polishing" but with a particle size of 0.5 μm for the second polishing. The experimental results of multiple machining of coated tools based on the MASJ principle are shown in Figure 2, and the surface morphology shown in Figure 3.

As shown in Figure 2, the surface roughness (Ra) of the KC5510 coated tool via one polishing is lower than that

Table 1 Single factor experimental scheme of KC5510 coated tool for MASJ polishing

No.	Incidence angle α (°)	Working pressure P (MPa)	Particle size W (μm)	Abrasive mass concentration ρ (g/L)	Nozzle diameter D (mm)	Stand-off distance S (mm)
1	15–90	0.4	1	75	0.5	7
2	45	0.2–0.6	1	75	0.5	7
3	45	0.3, 0.4	0.5–5	75	0.5	7
4	45	0.3, 0.4	1	50–125	0.5	7

of the untreated KC5510 coated tool, but higher than that via two polishing. As the surface quality improved, the coating removal thickness increased gradually, and the removal thickness of the coating was 0.51 μm after two polishing. Figure 3 shows the surface topography of the coating tools after multiple processing. The untreated coating surface comprised a large droplet; however, after one polishing, most of the droplets on the coating surface were removed. After two polishing, numerous white alumina particles were discovered, which were abrasives used in MASJ technology. By comparison, the surface quality of the coating improved after two polishing, where the coating became thinner, and the alumina particles were embedded in the coating surface. To investigate the effect of three different coatings on the tool performance, a turning experiment of hardened steel using the coated tool was designed.

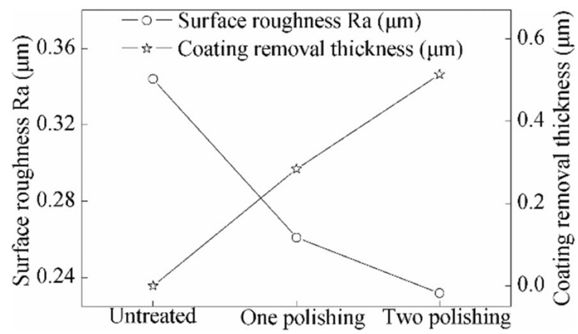

Figure 2 Results of applying MASJ in multiprocess machining of coated tools

2.3 Cutting Performance Evaluation Experiment

The research objects in the cutting experiment were CAXMAX hardened steel (manufactured by ASSAB Group®) with a length of 100 mm and a diameter of 61.5 mm. The chemistry constituents and hardness of the hardened steel are listed in Table 2.

The coated tool used in the test was a turning insert (CNMG120408MS KC5510, United States Kennametal). The substrate of the insert was composed of cemented carbide with grain refinement, in addition to an advanced PVD Al65Ti35N coating, whose hardness was 2800–3300 HV and average coating thickness 2.87 μm. The KC5510 tool was custom designed for the high-efficiency processing of high-temperature alloys with high toughness.

Prior to machining, a tool wear test was performed. The test was performed every 1 min (the cutting length was approximately 90 m), and the number of machining operations was recorded as "1 time" for each measurement. The phenomenon of collapse knife appeared at 40 times of turning, when the parameters were as follows: feed rate, $f = 0.4$ mm/r; cutting depth, $a_p = 0.25$ mm; cutting speed, $v = 90$ m/min; flank wear, $V_B \sim 60$ μm. Using the

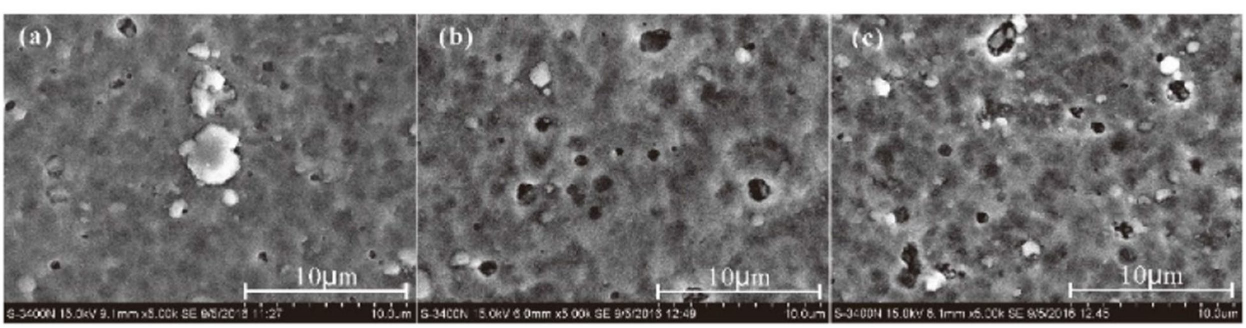

Figure 3 Surface topography of coating tools after multiple processing: (**a**) Untreated, (**b**) One polishing, (**c**) Two polishing

Table 2 Chemical compositions and hardness of workpieces

Material version	Chemical component (%)						Hardness (HRC)
	C	Si	Mn	Cr	Mo	V	
CAXMAX	0.6	0.35	0.8	4.5	0.5	0.2	52–54

Table 3 Cutting experiment program

No.	Cutting speed v (m/min)	Cutting depth a_p (mm)	Feed rate f (mm/r)
1	50–130	0.15	0.3
2	90	0.1–0.3	0.3
3	90	0.15	0.15–0.35

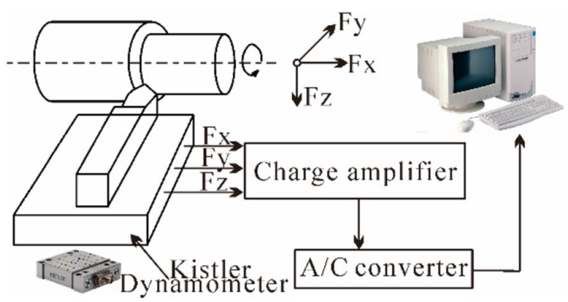

Figure 4 Schematic illustration of turning experiments

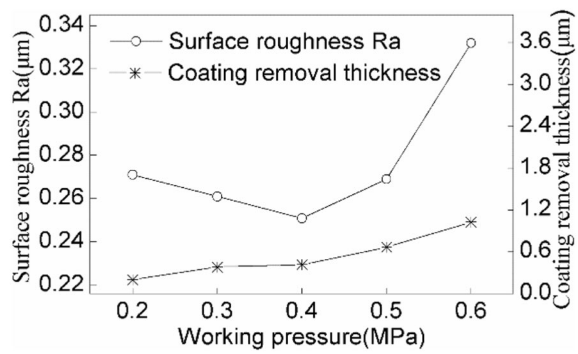

Figure 5 Effect of working pressure on surface roughness and coating removal thickness

same parameters for a new workpiece, defect appeared at approximately 20 times of turning, and V_B was approximately 40 μm. Hence, a_p was set to 0.15 mm, which resulted in collapse at 58 times of turning. Meanwhile, machining for 50 times with $a_p=0.1$ mm did not affect V_B and the rake face. Therefore, we selected medium-cutting test parameters for our wear experiments, i.e., cutting speed $v=90$ m/min, $a_p=0.25$ mm, and $f=0.3$ mm/r. V_B was measured approximately every 1 min after the test began until the turning length exceeded 1440 m. Owing to the limited clamping length of the lathe and the small diameter of the bar during turning, the actual turning length per minute was converted based on the experimental diameter of the bar and the Z-axis cutting length.

We used v, a_p, and f as the experimental factors, and five values from each factor were selected to design an experimental program for cutting. Each experiment was performed to test the cutting force and the Ra of the workpiece in real time per minute. The experimental parameters are shown in Table 3. The experimental parameters for each set were tested thrice, and the average values of the three measurements were recorded.

The turning experiment was performed on a CAK3665NJ Computer numerical control (CNC) lathe (spindle motor power = 5.5 kW; maximum spindle speed = 2400 r/min; GSK980TD system, Guangzhou NC). Additionally, dry cutting was performed. Figure 4 shows a schematic illustration of the turning experiments.

In the single-factor experiment of machining, the four sides (two rake faces and two flank faces) of turning coated inserts were machined surfaces, and the processing area was 6 mm × 6 mm. Meanwhile, in the combination experiment, only the flank face was selected for machined surfaces. During turning, the chip and tool are in close contact on the flank face, which will result in a higher cutting temperature and a failed tool. Hence, only the flank of the coated tool was polished in this study; polishing experiments for other areas will be performed in future studies.

In the turning insert polishing experiment, a surface profiler (MarSurf XR20), laser scanning confocal microscope (OLS4000), and scanning electron microscope (NOVA NANOSEM 430) were used to measure the surface roughness Ra, three-dimensional surface topography, and coating thickness, respectively; subsequently, a curve showing the relationship between the coating removal thickness and surface quality was obtained using the process parameters. A force measuring instrument (Kistler9129AA) was used to obtain the relationship between the cutting forces and cutting parameters.

3 Results and Discussion

3.1 Single-Factor Experiment of MASJ Polishing KC5510 Coated Tool

3.1.1 Working Pressure

Figure 5 shows the effect of the working pressure on the Ra and coating removal thickness. As shown in Figure 5, the Ra of the coated tool first decreases and then increases as the working pressure increases. At approximately 0.4 MPa, the coating surface quality is optimal. A linear relationship exists between the impact force of a jet and the working pressure [25]. When the pressure is low, owing to the low impact force of the jet, the workpiece surface coating cannot be removed completely. Consequently, the original rough tool surface is not fully processed, and the Ra is high. As the working pressure increases, the surface of the workpiece is uniformly removed, and hence the surface quality is improved. However, when the pressure increases, the coating removal thickness of the surface of the workpiece increases. In this study, the coating removal thickness was 1.027 μm when the pressure was 0.6 MPa (see Figure 5). This is primarily because of the increase in the working pressure, which caused the kinetic energy of the abrasive particles to increase, and hence an improvement in the grinding ability of the abrasive particles on the workpiece. Furthermore, the effect of the jet by air becomes more significant, i.e., infiltration occurs between the jet body and air, and the jet kinetic energy diverges from the center to the surrounding. The inhomogeneity of the material removal is enhanced, and the texture is rough and uneven [26]. We observed that the coating of some areas had peeled off, and the Ra after treatment increased. The coating removal thickness increased with the working pressure, as shown in Figure 5. Figure 6 shows the surface morphology of the coating as the working pressure changes. We discovered that the workpiece was more uniform when the working pressure was 0.4 MPa, and that bumps and pits appeared on the coating surface when the pressure was 0.6 MPa. Additionally, the quality of the workpiece surface was unacceptable.

To ensure a higher Ra and less coating removal, the pressure should be less than 0.4 MPa, whereas the other parameters are unchanged.

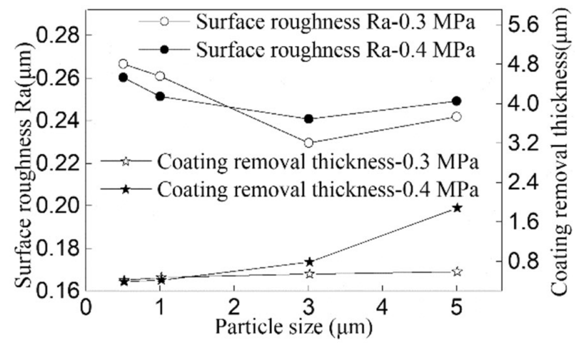

Figure 7 Effect of particle size on surface roughness and coating removal thickness

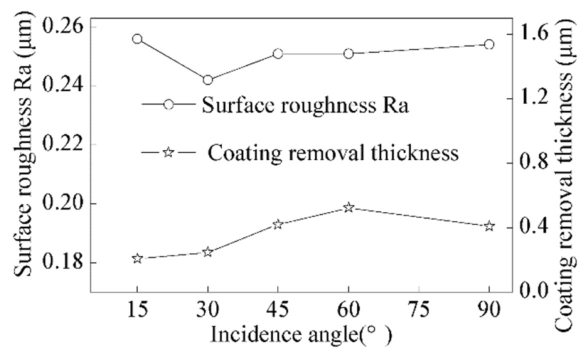

Figure 8 Effect of incidence angle on surface roughness and coating removal thickness

3.1.2 Particle Size

Figure 7 shows the effect of particle size on the Ra and coating removal thickness. The Ra first decreased and then increased as the particle size increased. When the working pressure was 0.3 MPa, the Ra increased from 0.229 to 0.242 μm when the particle size increased from 3 to 5 μm, which is consistent with the effect of particle size on Ra in conventional grinding and polishing. However, the Ra was higher when the particle size was 0.5 and 1 μm, as compared with that for 3 μm, which is opposite to the effect of particle size on Ra in the conventional grinding and polishing. This is primarily because at the ultralow working pressure, the particle is extremely small, the kinetic energy of the abrasive low, the grinding on the coating surface is weak, and the material removal

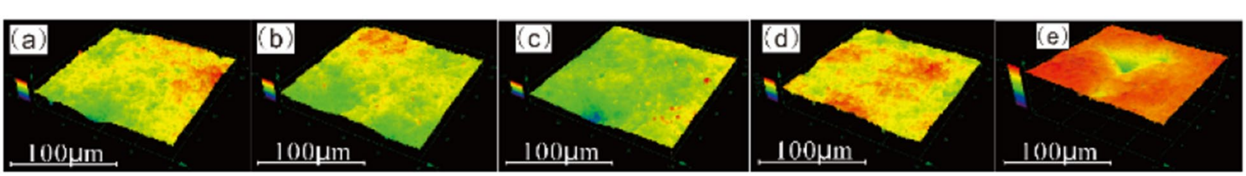

Figure 6 Effect of working pressure on surface topography: (**a**) 0.2 MPa, (**b**) 0.3 MPa, (**c**) 0.4 MPa, (**d**) 0.5 MPa, (**e**) 0.6 MPa

rate is low. Therefore, the effect of the MASJ on the Ra of the coating is limited. Hence, the surface quality afforded by the 0.5 and 1 μm particles was better at 0.3 MPa than at 0.4 MPa. Additionally, the coating removal thickness increased with the particle size, as shown in Figure 6. The removed thickness at 0.4 MPa was significantly larger than that at 0.3 MPa for particle sizes of 3 and 5 μm. Meanwhile, the removal thickness at 0.4 MPa was slightly larger than that at 0.3 MPa when the particle sizes were 0.5 and 1 μm; however, the difference was slight and thus can be regarded as experimental error.

3.1.3 Incidence Angle

Figure 8 shows the effect of the incidence angle on the Ra and coating removal thickness. The Ra of coated tool first decreased and then increased as the incidence angle increased, whereas the coating removal thickness first increased and then decreased.

The material removal rate increased as the incidence angle increased between 15° and 90°. When the incidence angle was between 45° and 60°, the highest material removal rate was recorded, which then decreased gradually. This trend is consistent with the results reported in Ref. [27]. Based on the study presented in Ref. [27], the authors of Ref. [26] further investigated the removal mechanism of the MASJ at different angles based on a plastic material. The result showed that the erosion mechanism of the MASJ was associated with the impact force of the particles on the tangential and normal direction of the workpiece. When the impact angle was less than 15°, the main erosion modes were shallow plowing and particle crimping; when the impact angle was greater than 15° and less than 75°, the main erosion mode was micro-cutting and deep plowing; when the impact angle was greater than 75° and less than 90°, pits and ridges significantly affected the material removal.

When the jet angle $\alpha = 15°$, the shear effect of the particles on the workpiece surface was insignificant, the coating removal thickness was small, the Ra value was high (see Figure 8), and the surface of the coating was susceptible to scratches. When the jet angle was 30°–45°, the jet exerted a significant shear effect on the workpiece surface; therefore, the coating removal thickness was larger, and the Ra was lower. When the incidence angle was 60°–90°, the jet exerted a significant plastic extrusion effect on the workpiece surface owing to the short processing time [28]. However, the shear effect was insignificant; therefore, the coating removal thickness was small, the Ra was high. The incidence angle is an important parameter in the post-treatment of the coating. To control the coating removal thickness, the required machining surface can be obtained via multiple processing with different incidence angles [29]. For the slurry jet polishing of multiple processes, the best injection angle is 30°–45°.

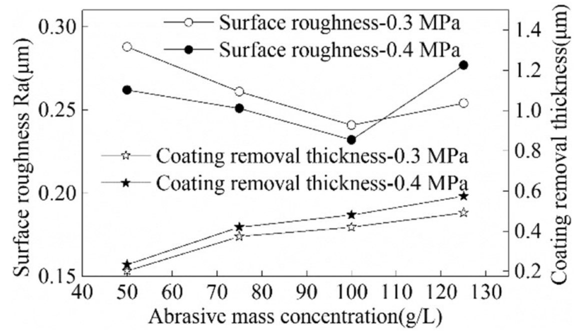

Figure 9 Effect of abrasive concentration on surface roughness and coating removal thickness

3.1.4 Abrasive Mass Concentration

Abrasive mass concentration refers to the mass content of abrasives in a unit volume. Zu et al. [30] discovered that interactions between abrasive particles are negligible in the entire machining process if the abrasive concentration is less than 1 kg/L. Figure 9 shows the effect of abrasive concentration on the Ra and coating removal thickness.

As shown in Figure 9, the Ra decreased from 0.288 to 0.241 μm as the abrasive mass concentration increased from 50 to 100 g/L at 0.3 MPa. When the abrasive concentration increased from 100 to 125 g/L, the Ra increased gradually to 0.254 μm, which indicates that there was an optimal abrasive mass concentration to minimize Ra. Under the experimental conditions, the surface quality of the workpiece was the best when the abrasive mass concentration was 100 g/L. In the low abrasive concentration, the workpiece surface removal capacity was insufficient; consequently, the quality of the workpiece surface was low. However, as the concentration increased, the material removal rate increased and the workpiece surface readily formed a deep groove, which resulted in a rough workpiece surface. Hence, an optimal abrasive concentration exists to achieve the desired surface quality of the coated tools. The surface quality at the pressure of 0.4 MPa was better than that 0.3 MPa when the concentration was 50 g/L; however, the quality at 0.4 MPa was worse than that at 0.3 MPa when the concentration was 125 g/L, which fully illustrates the effects of pressure and abrasive concentration on the surface quality.

As shown in Figure 9, the coating removal thickness increases with the abrasive mass concentration. This is because when the abrasive concentration is low, the unit volume of the polishing slurry contains less abrasive

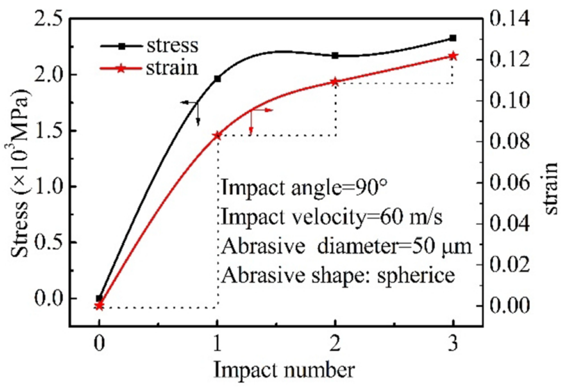

Figure 10 Effect of multiple impact on stress and strain [26]

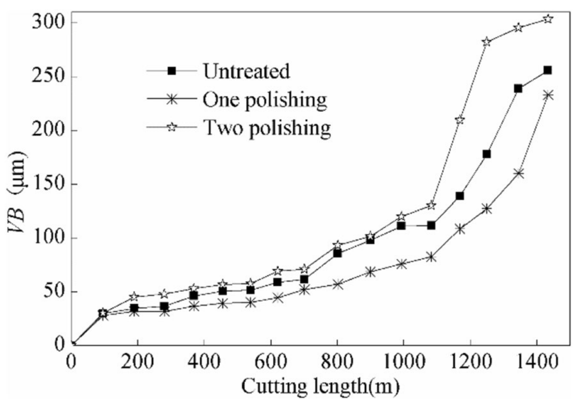

Figure 11 Wear curves of three types of coated tools

particles, the number of particles sprayed on the surface of the workpiece is few, and the removal rate of the material is relatively low under the same conditions, which proves that the MASJ machining depends primarily on the abrasive particles for removing the material. The higher the abrasive mass concentration, the more the number of abrasive particles involved in the impact per unit time. The coating removal thickness decreased gradually with the increase in the concentration primarily because the material removal rate of the workpiece is not proportional to the number of particles involved in the impact. Luo [26] discovered that the material removal rate after the impact of the first abrasive was much larger than those of the second and third. In this study, after the second and third abrasive grains were removed, the material removal rate decreased, and the material removal rate stabilized after the third abrasive impact, as shown in Figure 10. Therefore, when the abrasive mass concentration increased, the cumulative removal rate of the material increased and stabilized eventually.

As shown in Figure 9, when the abrasive mass concentration exceeds 100 g/L, the coating removal thickness exceeds 0.57 μm (working pressure = 0.4 MPa). Additionally, the decrease in the coating thickness will reduce the coating tool life, which should be avoided during the post-treatment of the coated tool. Therefore, in the combination experiment of MASJ, we should select a low abrasive mass concentration such that the Ra is low and the coating thickness would not be reduced significantly.

3.2 Single-Factor Experiment of MASJ Polishing KC5510 Coated Tool

The wear curves of the three tools shown in Figure 11 indicate that they undergo the initial, normal, and abrupt wear stages. The primary wear stage occurred when the cutting length was 0–180 m. At this stage, the cutting edge was sharp, the flank surface and processing surface contact area were small, and the compressive stress was high; furthermore, this stage was short. After the initial wear, the tool rough surface was smoothed. The normal wear stage occurred when the cutting length was 180–1260 m. The wear of the tool was slow and uniform at this stage, and the amount of flank wear increased proportionally with the cutting time. The cutting length was long in this stage. The abrupt wear stage occurred when the cutting length was 1260–1440 m. When the wear band width increased to a certain level, the surface became rough and the cutting force, cutting temperature, and wear rate increased rapidly. This resulted in damage to the cutting tool, the loss of cutting ability, and the end of the tool life. According to the International Organization for Standardization (ISO), the V_B for a carbide tool should be 0.3 mm such that the end of life of a tool occurs when the cutting length is approximately 1440 m.

As the cutting length increased, the amount of wear was the least from one polishing, whereas the amount of wear from two polishing was higher than that of the untreated coated tool (see Figure 11). When the cutting length was 1249.74 m, the wear amount of the untreated tool and those that underwent one and two polishing were 177.606, 127.464, and 282.372 μm, respectively. The wear amount of the tool with one polishing was 71.8% that of the untreated tool wear, and 45.1% that of the tool with two polishing. The performance of the tool with one polishing was superior to that of the untreated tool, primarily because the Ra of the coated tool after the MASJ treatment was lower than the uncoated tool. Hence, the cutting material did not adhere to the tool surface during the cutting process, which allowed the chip to separate from the tool rapidly and effectively, thus obviating the requirement for a high processing temperature. However, the two polishing tools were polished excessively, which resulted in a thin coating on the surface of the tool. Furthermore, because the coating droplets were removed, numerous alumina particles were embedded in the

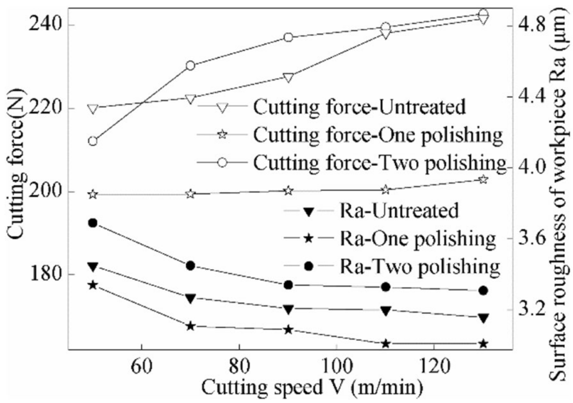

Figure 12 Effect of cutting speed on cutting force and surface roughness of workpiece

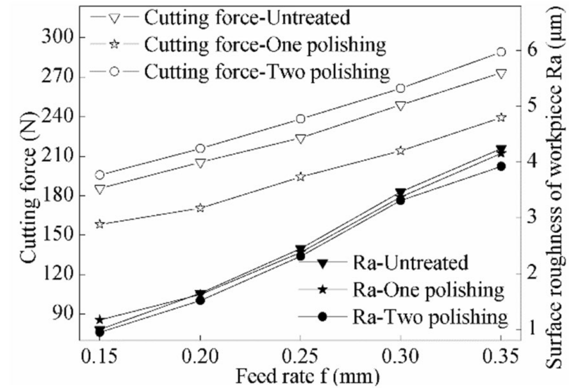

Figure 13 Effect of feed rate on cutting force and surface roughness of workpiece

coated tool surface, resulting in a stress concentration on the coated tool; additionally, the friction effect was more prominent, the cutting temperature increased, and the tool life reduced.

MASJ polishing can significantly improve the life of coated tools but requires a reasonable process.

3.3 Effects of Cutting Parameters on Cutting Force and Workpiece Surface Quality of Three Types of Cutting Tools

The cutting force typically refers to the force required to change the shape of a machined material after a tool cuts into a workpiece during metal cutting. The cutting force must overcome four aspects, i.e., the resistance of the elastic deformation of the material, the resistance of plastic deformation of the material, the friction of the chip against the tool rake face, and the friction of the flank surface of the cutting tool against that between the machined surfaces and unprocessed surfaces. The cutting force on the tool and machine tool, as well as the fixture design and use are important aspects. Many factors that affect the cutting force, such as the cutting parameters (v, f, and a_p), cutting tool geometry, materials, and tool wear.

3.3.1 Cutting Speed

The cutting force of the three types of tools increased gradually with the cutting speed (see Figure 12), primarily because a higher cutting speed results in a larger cutting output in unit time and a higher cutting force. However, the tool with one polishing tools did not change significantly, which indicates that it performed well although the cutting speed changed.

Among the three types of tools, based on the same cutting speed, the cutting force of the tool with one polishing was the lowest, whereas those of the tools with two polishing and without treatment were the same. The primary difference among the three types of tools was their surface quality. Hence, the surface quality of the coated tools significantly affects the cutting force. The quality of the tool with one polishing was better than that of the untreated tool, which indicates that the smooth flank of the tool with one polishing resulted in a low friction between it and the processed material surface. Meanwhile, for the tool with two polishing, the surface was embedded with alumina particles although the Ra was low, and the cutting force was high. This is primarily because as the process progressed, the friction of the tool surface caused the alumina particles to be released, resulting in a high friction between the flank face and machined surface.

As shown in Figure 12, after the three types of cutting tools cut into hardened die steel, the workpieces' Ra decreased as the cutting speed increased. Because CALMAX hardened die steels possess high toughness and hardenability, they can be used to produce continuous strip chips, which do not break easily at low cutting speeds. However, an excessively long chip will scratch the workpiece, thus increasing the Ra of the workpiece. Meanwhile, at high cutting speeds, the chip tends to break; furthermore, the heat softening effect of the workpiece enables good surface quality to be obtained. However, the Ra of the workpiece machined using the tool with one polishing was the lowest among the three types of tools, and the highest Ra was achieved using the tool with two polishing. This indicates that the post-treatment of the tools via MASJ technology affects the workpieces' surface quality and does not reduce the Ra of tools; hence, a high workpiece surface quality is achieved. Meanwhile, we discovered that the effects of the three types of tools on the surface quality of the workpiece were the same as that of the cutting force under the same

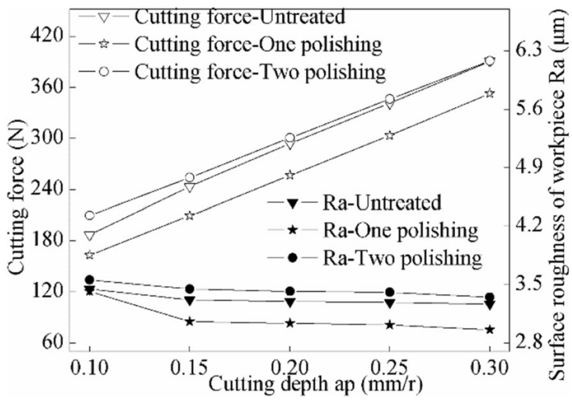

Figure 14 Effect of cutting depth on cutting force and surface roughness of workpiece

cutting speed. The smaller the cutting force, the better was the surface quality.

3.3.2 Feed Rate

As the feed rate increases, the removed width of the material increases in unit time. Therefore, a higher cutting power is required to remove more material, and as the feed increases, the cutting force will increase, theoretically. The cutting force linearly increased approximately linearly with the feed rate, whereas the force of the tool with one polishing was the smallest under the same feed rate (see Figure 13). The influencing factor is the same as that pertaining to the effect of the cutting speed on the cutting force.

Meanwhile, the Ra of the workpiece increased with the feed rate, and it increased approximately linearly after three types of tools cut into hardened die steel (see Figure 13). When the feed rate was relatively high and the other processing parameters remained unchanged, the repeated cutting probability of the material decreased. When the residual height of the workpiece was relatively large, groove marks were indicated on the surface of the workpiece; hence, the Ra was high. Additionally, the effect of the feed rate of the three types of tools on the surface quality of the workpiece was similar. More specifically, the tool with one polishing performed slightly better than the other tools, which is consistent with the effect of the feed rate on the cutting force.

3.3.3 Cutting Depth

As the cutting depth increases, the material removal increases in unit time; this implies that higher levels of the cutting power and cutting force are required. The result shows that the cutting force increased with the cutting depth (see Figure 14). The force of the tool with one polishing was the smallest for a fixed cutting depth, and the influencing factor was the same as that pertaining to the effect of the cutting speed on the cutting force.

The Ra of the workpiece decreased as the cutting depth increased after the three types of tools cut into the hardened die steel (see Figure 14). When the cutting depth was small, primarily owing to the cutting by the arc of the tooltip, the arc edge was not comparable to the general cutting edge in terms of sharpness, and the forepart of tool tip demonstrated high resistance. The strong squeeze effect between the tool arc and workpiece strengthened the plastic deformation of the workpiece. The relatively small cutting depth can result in a continuous chip that do not break easily; however, the excessively long chip envelopes the workpiece and rubs against the processed surface, which can increase the Ra of the workpiece. When the cutting depth increased gradually, cutting primarily occurred in the vicinity of the main cutting edge, and the squeeze effect between the tool and workpiece weakened. Meanwhile, the chip was no longer continuous, and the friction between the workpiece and chip was relatively low. Therefore, in a certain range, when the cutting depth increased, the workpiece Ra decreased. However, when the cutting depth further increased, the cutting force increased significantly during cutting, the cutting temperature increased, and the vibration of the workpiece increased; hence, the Ra increased. Because of the difficulty in cutting hardened die steels, the Kenner KC5010 series of cutting was adopted for semi-finishing and finishing processing. The five levels of cutting depth in the experiment were relatively low; therefore, the Ra of the workpiece decreased immediately after the cutting depth increased.

4 Conclusions

In this study, single-factor and combination experiments were performed on MASJ polishing coated tools. Based on the effects of the tool wear and cutting parameters on the cutting force and Ra, we discussed the cutting performance of three types of tools cutting into hardened die steels. The main conclusions are as follows:

(1) In the single-factor experiments, the Ra of the coated tools first decreased and then increased as the working pressure, particle size, incidence angle, and abrasive concentration increased. In the experiment, the best Ra was obtained when the pressure was 0.4 MPa, particle size was 3 μm, incidence angle was 30°, and abrasive concentration was 100 g/L. The coating removal thickness increased with the working pressure, particle size, and abrasive concentration, whereas it first increased and then decreased as the incidence angle increased.

(2) Based on the combination experiments, the Ra of the tool with two polishing was the highest, followed by that of the tool with one polishing. The coating thickness of the tool with two polishing was the smallest, and its surface was embedded with numerous alumina particles.
(3) Based on the cutting tool wear experiment and the parameters of cutting, we discovered that under the same conditions, the tool with one polishing yielded the best workpiece surface quality, whereas that with two polishing yielded the worst. The cutting force increased with the cutting speed, the feed rate, and cutting depth in the experiment. Furthermore, the Ra of the workpiece decreased as the cutting speed and cutting depth increased, whereas it increased with the feed rate.

Based on our results, MASJ technology can significantly improve the service life of coated tools, although an involved jet processing process is necessitated. In the future, we will investigate the removal mechanism of MASJs in regard to coated tools, the edge preparation of coated tools, and the process database of MASJs for coating cutting tools.

Acknowledgements
Not applicable.

Authors' Contributions
CW was responsible for the overall planning of the manuscript; RW completed the experiments and data analysis, as well as completed the writing, revision, and editing of the manuscript. All authors have read and approved the final manuscript.

Authors' Information
Rongjuan Wang Born in 1982, is currently a lecturer at *Airport College, Binzhou University, China*. She received her PhD degree from *Guangdong University of Technology, China*, in 2018. Her research interests include jet machining technology and ultrasonic machining technology.
Chengyong Wang Born in 1964, is currently a professor at *Guangdong University of Technology, China*. He received his PhD degree from *Dalian University of Technology, China*, in 1989. His research interests include machining of difficult-to-cut materials, micro-drilling of PCB composites, coated tool design and preparation, medical instruments design and manufacturing, laser machining and 3D printing.

Funding
Supported by National Natural Science Foundation of China (Grant No. 51735003), Research Start-up Fee for Doctoral Personnel of Binzhou University of China (Grant No. 2019Y12), and Key Program of NSFC-Guangdong Joint Fund of China (Grant No. U1201245).

Declarations

Competing Interests
The authors declare no competing financial interests.

Received: 22 February 2021 Revised: 4 September 2023 Accepted: 13 September 2023
Published online: 01 November 2023

References
[1] V Mehta, R Kumar, H Kumar. *Performance of composite coating on cutting tools: Coating technologies, performance optimization, and their characterization: A review*. Singapore: Springer Press, 2020.
[2] X C Wang, C C Wang, C Y Wang, et al. Approach for polishing diamond coated complicated cutting tool: Abrasive flow machining. *Chinese Journal of Mechanical Engineering*, 2018, 31: 97.
[3] K D Bouzakis, P Charalampous, T Kotsanis, et al. Effect of HM substrates' cutting edge roundness manufactured by laser machining and micro-blasting on the coated tools' cutting performance. *CIRP Journal of Manufacturing Science and Technology*, 2017, 18: 188–197.
[4] E E Yunata, T Aizawa, K Tamaoki, et al. Plasma polishing and finishing of CVD-diamond coated WC (Co) dies for dry stamping. *Procedia Engineering*, 2017, 207: 2197–2202.
[5] Y F Qin, H J Zhao, C Li, et al. Effect of heat treatment on the microstructure and corrosion behaviors of reactive plasma sprayed TiCN coatings. *Surface and Coatings Technology*, 2020, 398:126086.
[6] Z Yu, Y J Dong, G M Zheng, et al. Influence of micro sandblasting on the surface integrity of the AlTiN-coated tools. *The International Journal of Advanced Manufacturing Technology*, 2022, 120: 1359–1372.
[7] Z Yu, G M Zheng, X Cheng, et al. Review on micro-blasting surface treatment technology for coated tool. *Machine Tool & Hydraulics*, 2021, 49(18): 166–172.
[8] K Hang, G Zheng, X Cheng, et al. Surface integrity evolution and wear evolution of the micro-blasted coated tool in high-speed turning of Ti6Al4V. *The International Journal of Advanced Manufacturing Technology*, 2021, 115: 603–616.
[9] C Puneet, K Valleti, A V Gopal. Influence of surface preparation on the tool life of cathodic arc PVD coated twist drills. *Journal of Manufacturing Processes*, 2017, 27: 233–240.
[10] R Mundotia, D C Kothari, A Kale, et al. Effect of ion bombardment and micro sandblasting on the wear resistance properties of hard TiN coatings. *Materials Today: Proceedings*, 2020, 26(2): 603–612.
[11] Q L Liu, L H Zhu, Z Y Liu. Effect of micro-blasting post-treatment on the friction and wear properties of Ti N/MT-Ti CN/Al2O3/Ti OCN multilayer coatings. *Surface Technology*, 2019, 48(7): 371–377. (in Chinese)
[12] K D Bouzakis, S Gerardis, G Skordaris, et al. Effect of dry micro-blasting on PND-film properties, cutting edge geometry and tool life in milling. *Surface & Coatings Technology,* 2009, 204: 1081–1086.
[13] B Saleh Abusuilik. Pre-, intermediate, and post-treatment of hard coatings to improve their performance for forming and cutting tools. *Surface & Coatings Technology*, 2015, 284: 384–395.
[14] S B Abusuilik, K Inoue. Effects of intermediate surface treatments on corrosion resistance of cathodic arc PVD hard coatings. *Surface & Coating-sTechnology*, 2013, 237: 421–428.
[15] S Tanaka, T Shirochi, H Nishizawa, et al. Micro-blasting effect on fracture resistance of PVD-AlTiN coated cemented carbide cutting tools. *Surface & Coatings Technology*, 2016, 308: 337–340.
[16] C Liu, Z Liu, B Wang. Modification of surface morphology to enhance tribological properties for CVD coated cutting tools through wet micro blasting post-process. *Ceramics International,* 2018, 44: 3430–3439.
[17] A Jacob, S Gangopadhyay, A Satapathy, et al. Influences of micro sandblasting as surface treatment technique on Properties and performance of AlTiN coated tools. *Journal of Manufacturing Processes*, 2017, 29: 407–418.
[18] K D Bouzakis, G Skordaris, S Gerardis, et al. The effect of micro-blasting procedures on the cutting performance of coated tools. *FME Transactions*, 2009, 37: 71–82.
[19] K D Bouzakis, F Klocke, G Skordaris, et al. Influence of dry microblasting grain quality on wear behaviour of TiAlN coated tools. *Wear*, 2011, 271: 783–791.
[20] K D Bouzakis, G Skordaris, E Bouzakis, et al. Optimization of wet micro-blasting on PVD films with various grain materials for improving the coated tools' cutting performance. *CIRP Ann. Manuf. Technol.*, 2011, 60: 587–590.
[21] K D Bouzakis, G Skordaris, E Bouzakis, et al. A critical review of characteristic techniques for improving the cutting performance of coated tools. *Journal of Machine Engineering*, 2017, 17: 25–44.
[22] T Shen, L Zhu, Z Liu. Effect of micro-blasting on the tribological properties of TiN/MT-TiCN/Al2O3 /TiCNO coatings deposited by CVD. *International Journal of Refractory Metals and Hard Materials*, 2020, 88:105205

[23] L Faksa, W Daves, W Ecker, et al. Effect of shot peening on residual stresses and crack closure in CVD coated hard metal cutting inserts. *International Journal of Refractory Metals and Hard Materials*, 2019, 82: 174–182.
[24] X C Liu, Z W Liang, G L Wen, et al. Waterjet machining and research developments: A review. *International Journal of Advanced Manufacturing*, 2019, 102(5–8): 1257–1335.
[25] R J Wang, C Y Wang, W Wen, et al. Experimental study on a micro-abrasive slurry jet for glass polishing. *International Journal of Advanced Manufacturing*, 2017, 89(1/4): 451–462.
[26] W S Luo. *Fluid properties of micro-abrasive slurry jet and Polishing mold steel*. Guangzhou: Guangdong University of Technology, 2011. (in Chinese)
[27] R Tarodiya, B K Gandhi. Experimental investigation on slurry erosion behavior of 304L steel, grey cast iron, and high chromium white cast iron. *Journal of Tribology*, 2019, 141(9): 091602–5.
[28] D Liu, T Nguyen, J Wang, et al. Mechanisms of enhancing the machining performance in micro abrasive waterjet drilling of hard and brittle materials by vibration assistance. *International Journal of Machine Tools and Manufacture*, 2020, 151:103528.
[29] Z R Qiang. *Research on the erosion mechanism and processing craft on curved surface by abrasive water jet polishing*. Wuxi: Jiangnan University, 2018. (in Chinese)
[30] J B Zu, G T Burstein, I M Hutchings. Comparative study of the slurry erosion and free-fall particle erosion of aluminum. *Wear*, 1991, 149: 73–84.