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ORIGINAL ARTICLE

Topography and microstructure of the cutting surface machined with abrasive waterjet

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Abstract Abrasive waterjet (AWJ) technology has been widely used for cutting materials in precision machining. The present paper reports the surface topography and microstructure of the cutting surfaces machined by AWJ. Four different kinds of ductile metallic materials were used for preparation of specimens. With the AWJ processing technique, smooth surfaces were easily obtained with a lower surface roughness about 2 to 3 μm. By comparing the microhardness of the specimens with the control surface sample obtained by wire electrodischarge machining, it is found that there is no heat-affected zone on the cutting surfaces machined by AWJ. By observing the surface morphology and microstructure, the features of friction and wear marks are revealed. The results show that a smooth cutting surface is more easily obtained on hard materials, while erosions on soft material surfaces are more serious. All scratches have a clear consistent direction, under the action of mechanical abrasive wear.

Keywords Abrasive waterjet · Microcutting · Friction and wear · Surface topography

1 Introduction

As one of the fast-growing nontraditional machining technique, abrasive waterjet (AWJ) technology has had a continuously development process since 1970s [1]. With unique advantages [2, 3], such as good adaptability to various materials, no heat-affected zone, low-impact force on the workpiece, and friendliness to environment and users, AWJ machining technology has become one of the advanced machining techniques and has a good application prospect and an improved competitiveness in the field of modern manufacturing [4]. Summarizing the applied researches in recent years, we can see that the AWJ is a versatile tool used in almost all manufacturing processes, for instance, cutting, milling, forming, drilling, peening, cleaning, and coating removal [5].

In the AWJ machining process, ultrahigh-pressure water is used to accelerate abrasive particles sucked into a mixture chamber by the Ventury phenomenon from a hopper. Through an orifice and a focusing nozzle, the abrasive jet, in which the abrasive particles qualified to cut hard materials are carried, is formed with high speed and energy. Because the combined action of attack erosion and impact wear of jet-carried abrasive particles, the cutting surface is formed in a unique shape which is different from other mechanical processing surface. Because of its own speciality and uniqueness, many researchers focused on the establishment and description of the abrasive waterjet machining model in the past years. A lot of experimental and theoretical studies have been done to describe the principle and mechanism of the surface forming, and the prediction model of surface machining quality [6]. Based on these works, several macromorphology cutting models have been developed [7] as shown in Fig. 1. From the perspective of discriminating description in different areas, the cutting surface has been divided into four zones named as initial zone, smooth zone, transition zone, and rough zone, respectively. In order to reveal the details of impact of jet on the materials and removing materials of workpiece, many experts began to do further researches on the friction and wear effect of abrasive particles on the materials surfaces and established some theoretical models [8], such as "micro-cutting" model, "cutting-deformation" model, "ploughing-deformation" model, elastic model, elasticplastic model, etc.

In order to explore the machining process, Hashish [9] conducted a visualization experiment to observe the AWJ

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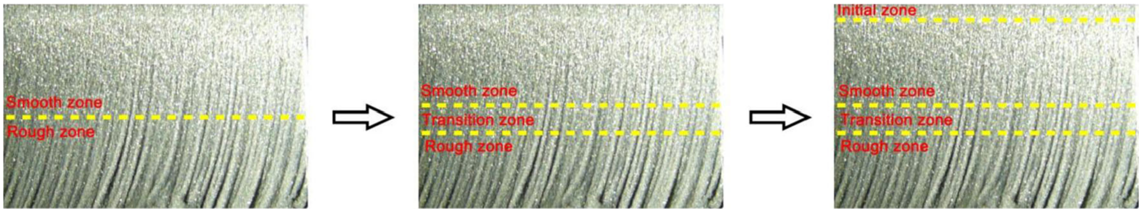


Fig. 1 The development process of the AWJ machining surface models

machining process by using a movie camera and find cutting-wear mode and deformation-wear mode which consists in the cutting process. Using the same method, Orbanic [10] studied the macromechanism of AWJ cutting and analyzed the striation formation on the machined surface. In the macroscale, the surfaces and kerfs characteristics of AWJ cutting pieces are the most significant features [11], especially for some difficult-to-machine materials, such as composite materials [12, 13], titanium alloy [14], and hard-brittle materials [15]. For obtaining a better surface quality, Boud [16] argued the influence of properties of abrasives on the machined surface of workpieces; Khan and Haque [17] discussed the performance of different abrasive materials on the taper and width of cut during the AWJ machining. Kantha Babu [18] used single-mesh-size abrasives to reduce the surface roughness of aluminum cutting surface in AWJ machining process. In this paper, the authors focused on the smooth zone and tried to do some deep research and analysis on the friction and wear phenomenon of the AWJ cutting surface in microscopic scale.

2 Experiments

In the AWJ machining process, the workpiece material is removed by the ultrahigh-pressure waterjet mixed with abrasive particles [19]. The surface quality are affected by the coactions of hydraulic pressure, traverse speed, stand-off distance, nozzle diameter, abrasive mass flow rate, and the quality of the abrasive [13–15]. Figure 2 showed a sample of the AWJ cutting surface under a light irradiated from left with an angle of 40°. Under the light, the striations were easily distinguished on the cutting surface of 304 stainless steel machined with AWJ under a pressure of 370 MPa and a traverse speed of 66 mm/min. Garnet was selected as abrasive materials in this simple cutting experiment. With the friction and wear effect of abrasive particles and the structural feature of the jets, macroscopic features of AWJ machining process were generated on the cutting surface, where we can distinguish the different areas of smooth zone, transition zone, and rough zone.

A cantilever-style abrasive waterjet cutting machine, the OMAX 55100 Precision Jet Machining Center, was used to prepare the specimens of metallic materials for surface testing. In order to get high-quality cutting surfaces, the machining process was under high pressure and at low traverse speed. Garnet obtained from India was selected as abrasive, with a sieve mesh size of #100, because of its optimum performance of cutting versus cost and its lack of toxicity. The details of machining process parameters are shown in Table 1. Four different kinds of metallic materials, 6061 aluminum alloy, 304 stainless steel, high-strength low alloy structural steel (Q345), and cold work mold steel (CrWMn), were chosen for preparation of specimens. An area of 8 mm×8 mm from the smooth zone of cutting surfaces was selected for measurement. Other areas of the AWJ machining surfaces were not discussed in the present work.

3 Results and discussion

In the AWJ machining process, the cutting surfaces of machined parts were obtained by the interaction with abrasive particles entrained in the ultrahigh pressure water jet. Before the jet ejected from the nozzle, abrasive particles gained a quantity of energy, which is the main power of the processing capacity, from the water during the mixing and accelerating process. These solid particles were distributed in the jet with

Fig. 2 Macrostructure of 304 stainless steel surface machined by AWJ (irradiated from the *left*)

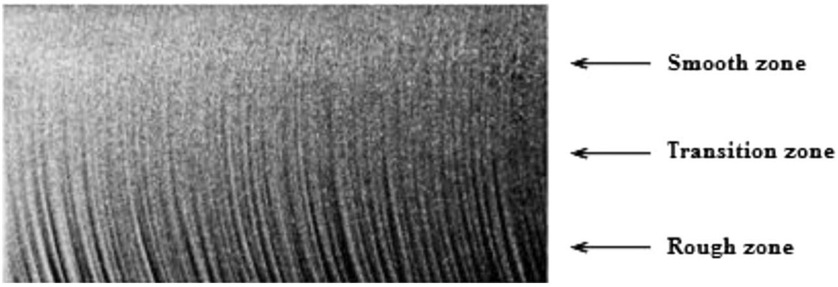


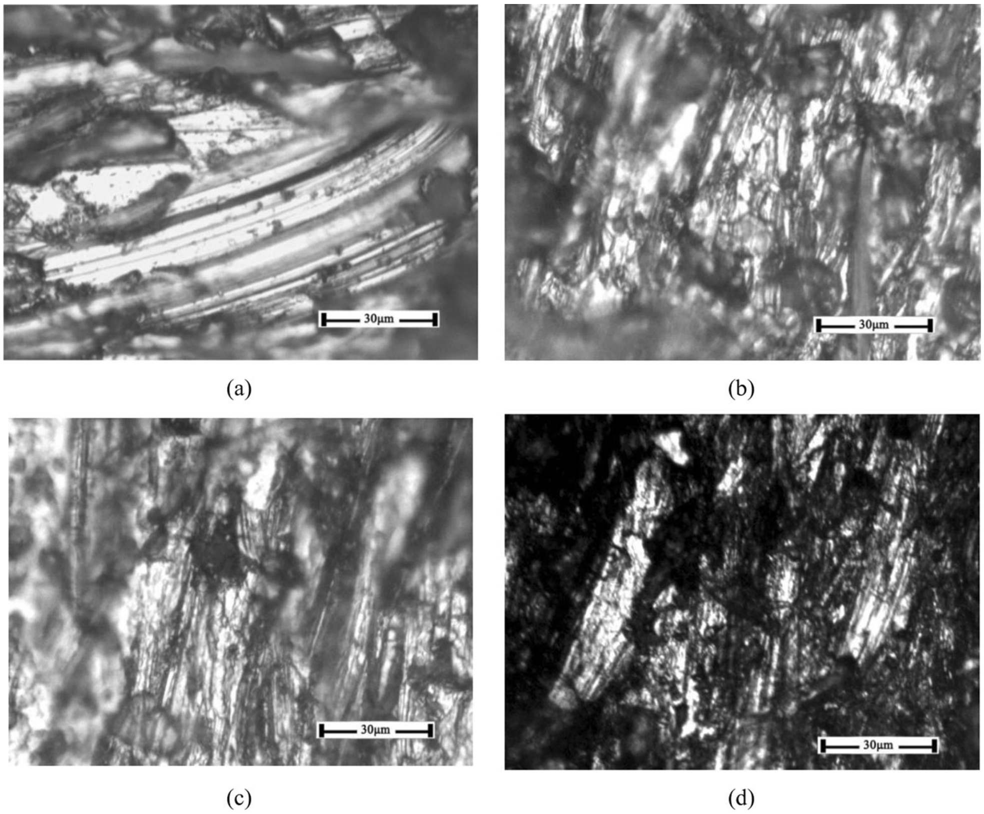
Table 1 Parameters of the AWJ machining process

Hydraulic pressure	55 kPSI
Traverse speed	66 mm/min
Orifice diameter	0.35 mm
Focusing nozzle diameter	0.75 mm
Stand-off distance	1.6 mm
Abrasive mass flow rate	0.33 kg/min
Sieve mesh size	#100

its unique rules. With the flow characteristics of the fluid itself, abrasive particles still have the opportunity for free motion on other directions different from the direction of jet, especially when affected by external factors. Meanwhile, the abrasive waterjet will be deflected, deformed, and diffused during the machining process.

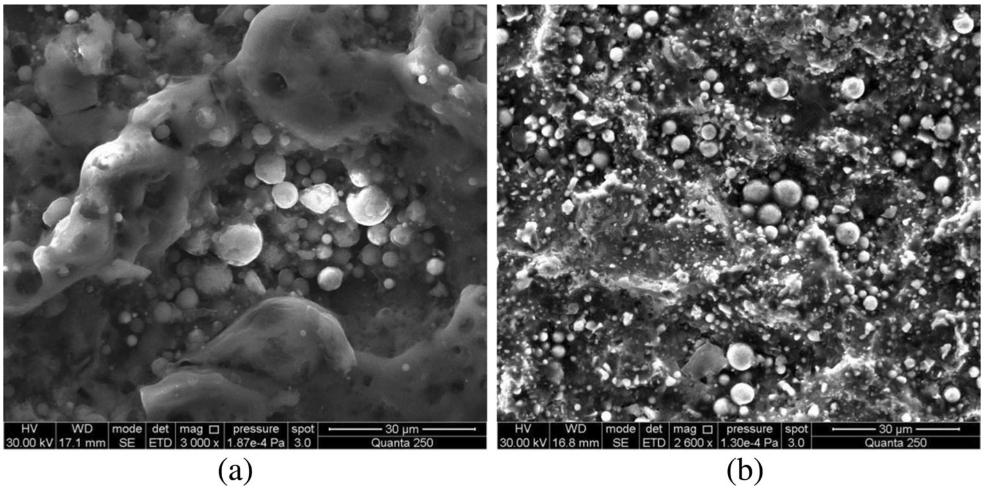
It can be easily noticed that the cutting surface is not smooth within the smooth zone by the light microscopy. All the details are revealed on original cutting surfaces clearly (shown in Fig. 3). Through the photos of microstructures, we can find traces of wear and friction by abrasive particles with high speed during the machining process. Some scratches are distinct and complete, and all of the scratches are short with a length of 100 μm around or less. Different from other kinds of mechanical friction, clear little crook and arc are a typical feature in the friction scratch. These nonlinear marks were formed because abrasive particles suspended in ultrahigh-pressure water are not rigidly connected with the jet and can move limitedly due to the liquidity of water. Because the impact time of the solid particles on the machined surface is short, the long and thin scratch has a deep pit in the middle and shallow cuts on both sides. Limited to the very shallow depth of field, the starting region of impact and the wake of the end of impact are blurring. As such, the metallic luster of every singular scratch can be significant under light microscopy.

The surface hardness of the material has been concerned in our machined surface characteristics discussion. A control sample of CrWMn, which is widely used in the field of mechanical processing, was prepared by using wire electrodischarge machining technique. The microhardness of this control sample is 299. As we know, in the wire electrodischarge machining (W-EDM) process, the metal melts and evaporates when the wire transiting the material and the melted metal will soon congeal under the action of coolant or dielectric liquid [20]. This process is similar to a surface hardening process [21]. Influenced by the cutting heat on the surface of materials, the increase of the surface hardness will always happen in processes of other kind of mechanical processing. At the end of this surface-hardening process, some melted materials solidify on the machined surface. The distribution of solidified tiny spheres was observed by means of scanning electron microscope, shown in Fig. 4. By means



(a) (b) (c) (d)

Fig. 3 Microstructure of four different materials machined by AWJ (the scale length is 30 μm). **a** 6061 Aluminum alloy, **b** 304 stainless steel, **c** Q345, high-strength low alloy structural steel, **d** CrWMn, cold work mold steel



(a) (b)

Fig. 4 SEM-images of **a** 6061 aluminum alloy and **b** CrWMn cutting surface machined by W-EDM

of microhardness testing, the Vickers hardness value of 6061 aluminum alloy surfaces machined by W-EDM is 80.

Table 2 lists the Vickers hardness of machined surfaces of the four different materials. For CrWMn, the microhardness of the surface machined by AWJ is less than that by the W-EDM. Compared with the 6061 aluminum alloy surface machined by W-EDM, AWJ machined surface also has low microhardness. On the surface of materials, the AWJ machining technique did not produce any heat-affected zone. Thermal distribution on workpiece during machining process was first measured by Ohadi [22], who found the temperature peaks rose up to 70 °C by using a matrix of thermocouples. Even if high temperatures occur upon the impact of abrasive particles on the target materials for very short periods of time, the heat generated by the interaction will be carried away be the water at the same time. As one of the biggest advantages of AWJ technology, it will keep the original properties of the material during the process. For monitoring the AWJ cutting process, this low temperature distribution has been measured by the means of infrared thermography [23].

The friction and wear morphology of the cutting surface is the result of the interaction between abrasive grinding grain and the material. The characteristics of the material, such as hardness, malleability, rigidity, and ductility, also have certain effects on the generation of the scratch. With the same cutting conditions, the sizes of scratches depend on the hardness of material. With optical technology, three-dimensional surface topography images of the four different materials were given in Fig. 5. When abrasive particles impact and remove materials at a low-impact angle, there are two main modes of material removal due to microcutting, such as cutting deformation and plough deformation. It is shown in Fig. 5a that traces of impact and erosion on the soft material surface (aluminum alloy) are deeper and more obvious than those on harder materials. The cutting surface of the cold work mold steel is relatively smooth, as shown in Fig. 5d. By measuring the surface roughness (Ra) of the machined surface, we can learn more important information about the wear condition in the machining process. It is known that the aluminum is an easy-processable material. In our experiments, the aluminum sample has the roughest cutting surface with a roughness of 4.23 μm, because abrasive particles erode and remove material on aluminum alloy surface more easily than on those difficult-to-machine materials. It is shown that a smooth cutting surface is more easily obtained on a hard material and erosions of a soft material surface are more serious (Table 3).

Table 2 Microhardness of machined surfaces for four different materials

Materials	Vickers hardness
6061 Aluminum alloy	40
304 Stainless steel	195
Q345, High-strength low alloy structural steel	147
CrWMn, Cold work mold steel	220

According to the microscopic pictures and three-dimensional images, we can see that the scratches have a clear direction. It is known that the high-speed and high-pressure jet, consisting of abrasive particles which play a major processing capacity, has an identified linear path during the machining process. It is speculated that all tracks on the cutting surface could have a consistent direction. And this speculation has been confirmed by the scanning electron microscope image, as shown in Fig. 6. The impact of a single abrasive grain is the basic event in the material removal by AWJ. The vast majority of removed material is directly below the jet and eroded by abrasive particles under a high impact angle. The target material can be effectively penetrated and removed by the jet. After completion of the cutting operation, we got a cutting surface where tracks were left after a series of erosion at a shallow impact angle. On the high-strength low-

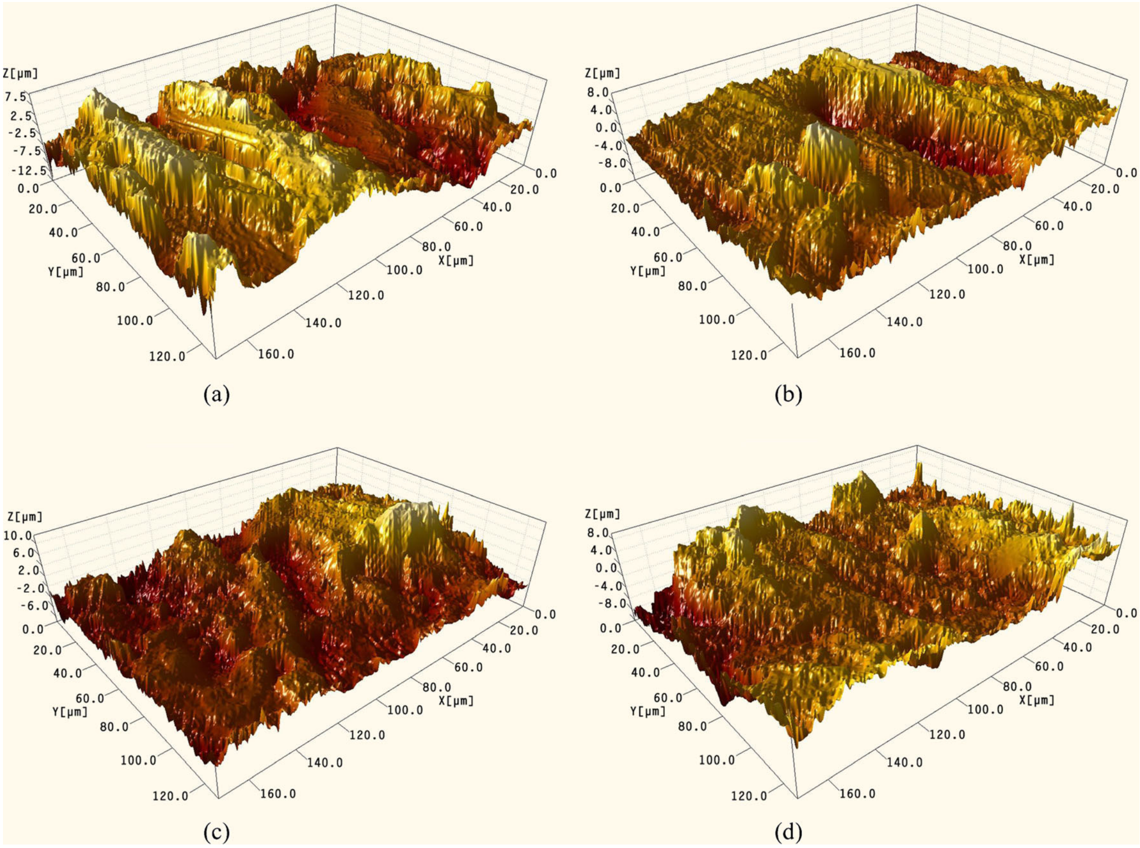


Fig. 5 Surface three-dimensional topography of four different materials machined by AWJ. **a** 6061 Aluminum alloy; **b** 304 stainless steel; **c** Q345, high strength low alloy structural steel; **d** CrWMn, cold work mold steel

alloy structural steel surface machined by AWJ, it exhibits a number of erosion curves with a unanimous direction. Some smaller craters are appealed in a large groove-shape scratch. Abrasive grains may erode the surface at the same position repeatedly so that wear marks can overlap each other and present an interleaved small angle.

In the field of mechanical processing, it is known that the machining parameters are completely different, in order to achieve the same surface finish, when the materials of machined parts are different. When AWJ technology is used for processing, researchers have conducted a great deal of research work to find the optimal machining parameters for different materials, respectively. In our work, only one set of machining conditions was used for the four kind materials.

Table 3 Roughness of machined surfaces of four different kinds of materials

Materials	Roughness, Ra (μm)
6061 Aluminum alloy	4.23
304 Stainless steel	1.37
Q345, High-strength low alloy structural steel	2.47
CrWMn, Cold work mold steel	1.53

The measurement results of specimens have been shown above. In Fig. 7, the surface of 6061 aluminum alloy machined by AWJ looks rough. It can be seen that scratches on

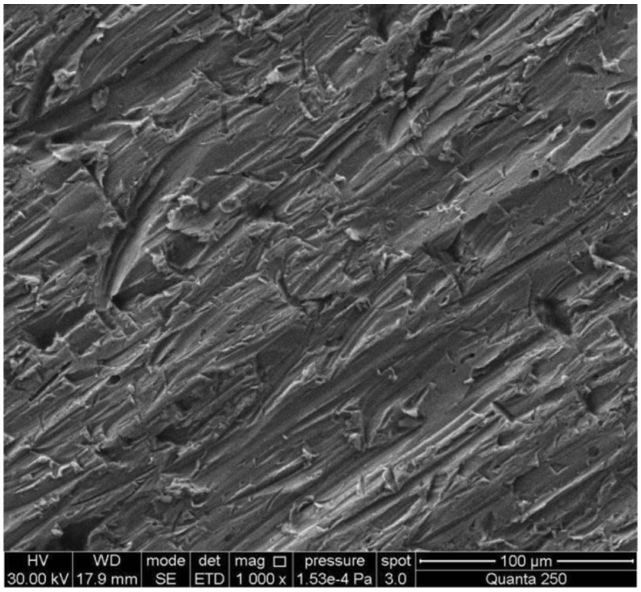


Fig. 6 SEM-image of Q345 cutting surface machined by AWJ in the smooth zone

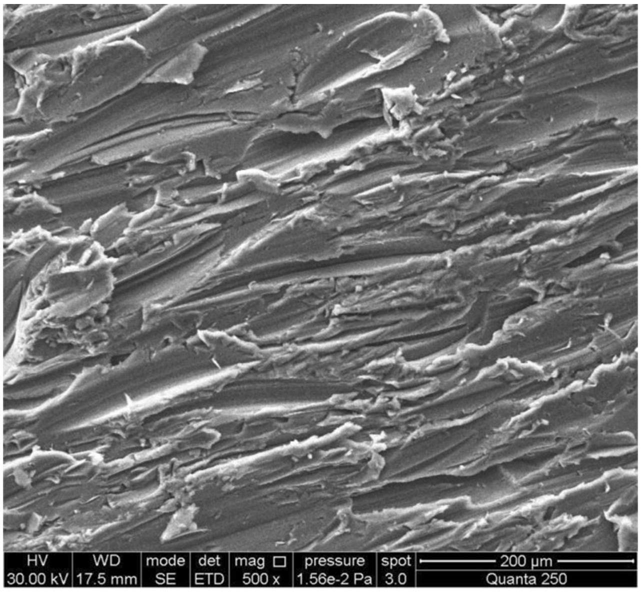


Fig. 7 SEM-image of 6061 aluminum alloy cutting surface machined by AWJ in the smooth zone

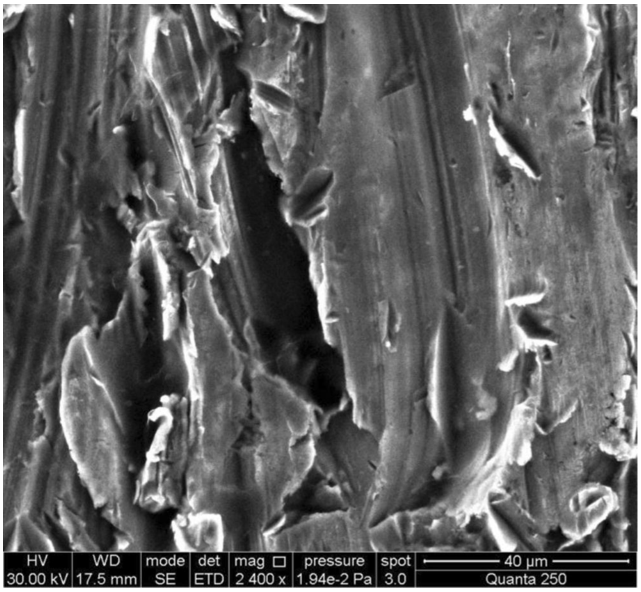


Fig. 9 SEM-image of 304 stainless steel machined by AWJ magnified by 2,400 times

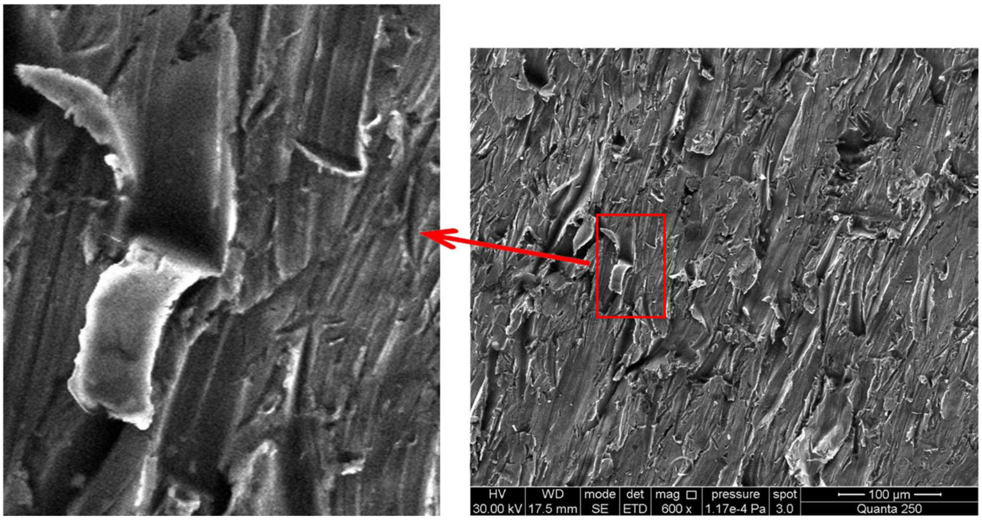
aluminum alloy surface are larger than that on Q345 surface. The roughness of 6061 aluminum alloy surface is the largest in this experiment for four different materials.

In Fig. 8, it is noticed that a lip on the lower end of the crater is preserved on the surface without removal by other abrasive particles and water jet. On its right side, there is an obvious mark that remained after the lip of this crater which is later removed by other impacting particles. As a result, a chip is generated. The summary of all these microchips determines the mass of removed materials. And a scratched surface is formed after this cutting process. In the experiment, the medium size of abrasive particles is 0.15 mm approximately. The size of scratches and grooves made by grains are from a few microns to dozens of micron, as shown in Figs. 6, 8, and 9. Scanning electron microscope images of AWJ machined surfaces show the typical features of scratches and grooves made by abrasive particles, and the size of these scratches and grooves are in a good correlation with particles sizes after the mixing process in the mixing chamber of the abrasive waterjet cutting head [24, 25].

4 Conclusions

AWJ machining technology is a fast-growing nontraditional machining technique and will have a good application prospect in the precision machining field. In this study, cutting surfaces of ductile materials machined by AWJ were tested

Fig. 8 SEM-image of a CrWMn specimen machined by AWJ with a cutting lip feature indicating the micro-cutting



and analyzed. All the results have shown its unique properties. Summarizing the main features of the results, the following conclusions may be drawn:

1. By measuring the roughness of the cutting surface, this kind of processing method fully complies with the general requirements of parts processing. One-time processing can be achieved by AWJ technique.
2. By the results of the microhardness of the machined surface, the hardness of the surface machined by AWJ is smaller than that by wire-EDM machined surfaces. Without heat-affected zone on the cutting surface, the AWJ technique can be used in the processing field which has higher requirements.
3. The mechanical abrasive wear is shown on the surface morphology. Scratches are formed under the action of microcutting and microploughing, and all of them have a clear consistent direction. In addition to the effect of the nature of water jet, friction and wear marks on the machined surface cannot be a completely straight line.
4. Under the same AWJ processing condition, the friction and wear degree on each kind of material is different. By measuring the cutting surface topography, all details of the cutting surface microstructure are presented. It shows that a smooth cutting surface is more easily obtained on a hard material and erosions of a soft material surface are more serious.

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