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ORIGINAL ARTICLE

An exploration of an abrasive water jet cutting front profile

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Abstract Abrasive water jet (AWJ) now is used as a precision cutting tool. With this tool, dimension tolerance less than 0.1 mm is expected in the cutting process. This dimension tolerance is enough for some applications. However, higher precision is necessary in order to use AWJ in some other applications. To get higher precision in an AWJ cutting process, controlling AWJ beam more accurately is needed, and this further leads to understanding AWJ cutting front more accurately. This paper compared the current cutting front profile exploration methods and then provided a new method to collect AWJ cutting front information accurately. With this new method, a better understanding of the cutting front profile is possible, which further leads to higher precision cutting of AWJ. This paper also demonstrated that the AWJ cutting front profile could be fitted by parabolic curves accurately.

Keywords Abrasive water jet · Cutting front profile · Dial indicator · Parabolic curve

1 Introduction

Abrasive water jet (AWJ) is one of the most recently developed manufacturing processes. In this process, clean water is pressurized to a very high pressure, which is as high as 420 MPa. The high-pressure water is then forced to come out from a very small nozzle. After it comes out from that nozzle, a high-speed water jet beam is formed. This high-speed water jet beam could be used to cut some soft materials, such as a paperboard or a sponge. If abrasive particles are added into that water jet beam, a high-speed abrasive jet beam is formed. This high-speed abrasive jet beam could be used to cut all kinds of materials. As a very promising manufacturing method, abrasive water jet has been used extensively in industry currently. Now, machine parts with tolerance less than 0.1 mm can be cut by AWJ directly. However, the further application of this technology has been limited by its cutting accuracy. In fact, much effort has been done to improve cutting accuracy and efficiency in the past years. For example, an accurate cutting model has been built to improve the cutting accuracy.

Unlike traditional manufacturing methods, in which the cutting accuracy is decided by the shape of the tool, the cutting accuracy of AWJ is not decided by a soft abrasive jet beam, which might bounce back and forth when it impacts on the target material, but decided by the AWJ cutting front. Therefore, understanding the cutting front of abrasive water jet beam is very important. In another word, the behavior of the cutting front is a major factor which affects the cutting process [1]. This paper investigated an effective method to catch cutting front information. With this method, the cutting front profile has been explored.

Lots of effort have been made to understand AWJ cutting front. In 1984, Hashish's visualization study by using high-speed camera to record the AWJ cutting process in a transparent workpiece material captured the curve shape of the cutting front and the cyclic nature of the cutting process [2]. Matsui found that the cutting front profile can be represented by an arc [3]. Zeng etched the striation marks on the cut surfaces and found that these can be well represented by parabolic curves [4]. Henning generated a surface scan of an abrasive water jet cut surface with an auto-focus sensor, and they found that the depth of striation was represented by six times of the standard deviation of each scan, indicating a parabolic curve below a straight line at the upper surface [5]. Then, they studied the impact of translational and rotary energy of abrasive particles to the curvature of the cutting front. They also analyzed the

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dynamics of the cutting front and showed a time series of local material removal rate along the cutting front based on their spatio-temporal model. Hlaváˇc measured the declination angles on their cutting samples and presented a declination angle prediction model [6].

The above efforts provided some very important information to understand abrasive jet cutting front. However, those methods mentioned above have some limitations which limited their applications. For example, surface scanning method could be used to catch accurate information when the striation marks are obvious, but, when cutting quality is good enough so that the striation marks cannot be recognized clearly, this method is not effective anymore. In order to catch cutting front information accurately, a new method has been explored and presented in this paper.

2 Experimental study

Without a doubt, AWJ cutting front performs differently as cutting parameters change. To find out how AWJ cutting parameters affect the cutting front, a series of experiments has been carried out.

2.1 Experimental design

As mentioned above, several cutting parameters affect AWJ cutting front. These parameters include water pressure, abrasive flowrate, abrasive type, abrasive mesh, nozzle combination, target material type, target material thickness, cutting speed, etc. To simplify the testing, garnet has been selected as the abrasive type and an 80-mesh size of abrasive particles has been used in this test. This is reasonable and feasible since more than 95 % of AWJ cutting is finished with garnet and 80 mesh is the regular particle size used in the AWJ cutting process. For the target material, aluminum 6061T is selected since this type of material is used widely in industry. Though nozzle combination is a parameter which definitely has an effect on the cutting front, a fixed one, 0.33 mm as the diameter for the water jet orifice and 0.89 mm as the diameter for the focusing tube, has been used this time. For other parameters, such as water pressure, abrasive flowrate, cutting speed, and target material, different numbers have been selected for each parameter in this test. In order to carry out less tests but get enough information, orthogonal experimental design method has been used in this test. And experimental parameters have been listed in Table 1.

Table 1 Orthogonal array L9 (34) for cutting test

Combination	Factor 1 Target material thickness (mm)	Factor 2 Water pressure (MPa)	Factor 3 Cutting speed
First	10	245	Q3
Second	10	315	Q5
Third	10	385	Q10
Fourth	25	245	Q5
Fifth	25	315	Q10
Sixth	25	385	Q3
Seventh	50	245	Q10
Eighth	50	315	Q3
Ninth	50	385	Q5

Fig. 1 Experimental process to get the separation speed

In Table 1, Q3, Q5, and Q10 represent cutting quality. Actually, cutting quality is related to cutting speed. In order to get the cutting speed, separation speed must be found firstly. Separation speed is the maximum speed to cut through the target material, which can be obtained with several steps. Firstly, cut a 50-mm-long straight line with a proper speed. Secondly, check out whether the target material is cut through or not. If the target material is not cut through, a lower speed needs to be tried until the target material is cut through.

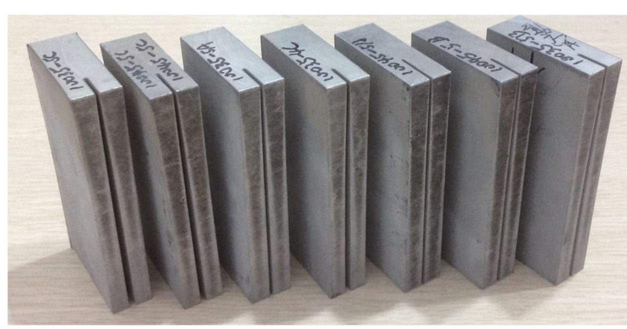

Fig. 2 Some samples cut by AWJ

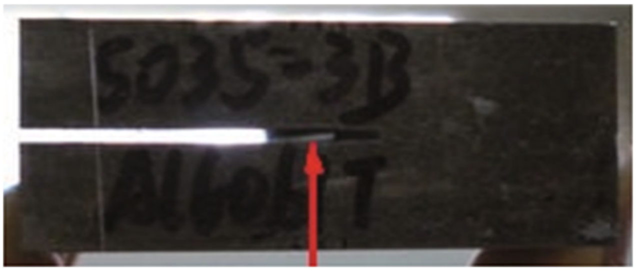

Fig. 3 Real cutting front profile (*top view*)

Thirdly, check out whether the bottom of the target material is cut through completely or not along the whole cutting path. If it is, a higher cutting speed needs to be tried until some discontinuous section presents on the whole cutting path. Fourthly, measure the length of the discontinuous sections until no one is longer than 1.5 mm. With the above four steps, the separation speed can be found out. A sample for separation speed testing is shown in Fig. 1.

After getting the separation speed, the cutting speed corresponding to quality index can be obtained. According to the cutting model by Zeng [7], the cutting speed is related to a quality index Q as follows:

$$U = \mathrm{Usep}/Q^{1.15}. \quad (1)$$

where Usep is the separation speed. In these tests, Q3 is 28.26 % of the separation speed, Q5 is 15.71 % of the separation speed, and Q10 is 7.08 % of the separation speed. With this method, the same cutting quality could be achieved. After finding the separation speed, it is ready for testing.

Actually, it is not easy to get cutting front information accurately. As we know, during any line cutting process, cutting front is related to cutting speed. And for any line cutting, the cutting head is moving in an acceleration phase, stable speed phase, and then a deceleration phase. In the acceleration phase and deceleration phase, it is hard to find the cutting speed corresponding to cutting front information. Therefore, cutting front information must be caught during stable speed phase,

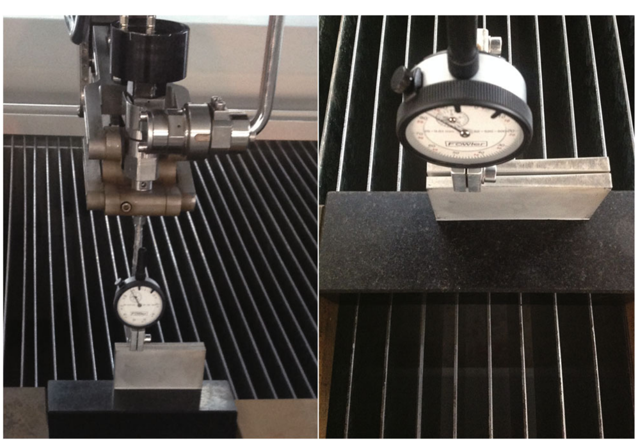

Fig. 4 The instrument used to measure the cutting front profile

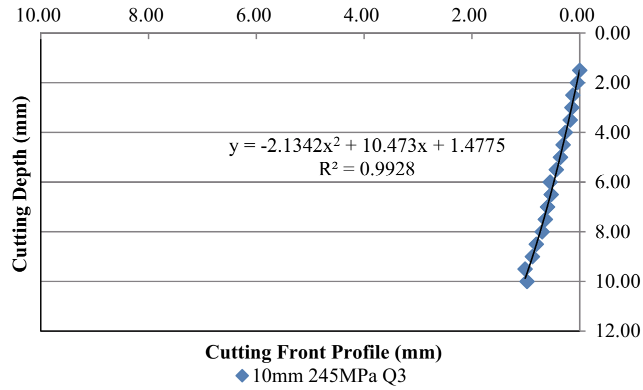

Fig. 5 Cutting front profile (10 mm 245 MPa Q3)

except that it is not right to catch cutting front information accurately by shutting down the abrasive valve, which is the method currently used. The reason for that is, at the moment of abrasive valve shutting down, some abrasive particles are still in the abrasive transporting hose. Those abrasive particles would change AWJ cutting front information. Because of this, the cutting front profile we get is not accurate anymore.

In order to get cutting front information accurately, a new method has been used. In this method, when the cutting process is in the stable phase, the abrasive transporting hose is pulled off from the nozzle connecting end. With this method, although the abrasive valve is not shut down, abrasive particles in the abrasive transporting hose would not affect the cutting front (Fig. 2).

2.2 Data collection

After getting samples, the next step is collecting cutting front information accurately. As we know, the kerf width cut by AWJ is usually less than 1 mm. With this small kerf width, it is not easy to get the cutting front profile accurately. To effectively measure the cutting front profile, the equipment shown in Fig. 4 was developed. A dial indicator was manually assembled in the cutting head. Furthermore, considering the kerf is deep and thin as shown in Fig. 3, the point set of the dial indicator was changed into a rigid needle in order to make sure the point set

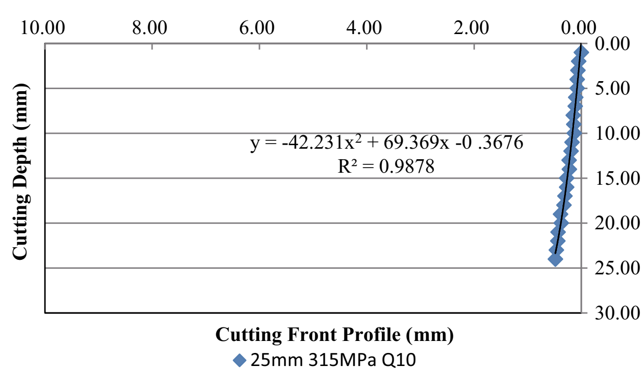

Fig. 6 Cutting front profile (25 mm 315 MPa Q10)

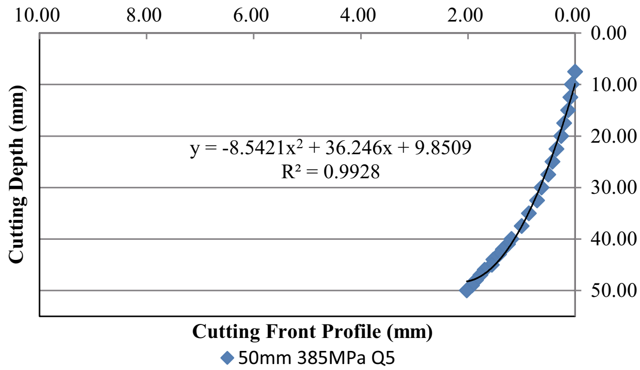

Fig. 7 Cutting front profile (50 mm 385 MPa Q5)

could contact the surface of the cutting front. And then by moving the dial indicator along the cutting front profile, cutting front information can be obtained accurately (Fig. 4).

3 Result and discussion

In order to get cutting front information accurately, 15 to 25 points along the cutting front have been collected along the cutting front profile by using a dial indicator. With these data, a series of cutting front profiles has been obtained accurately.

From Figs. 5, 6, and 7, the cutting front profiles obtained from the dial indicator test and parabolic curves are in very good agreement. This observation confirmed that the profiles of the cutting front are real parabolic curves.

4 Conclusions

Based on the above analysis, the following conclusions can be reached:

1) The cutting front information could be caught by pulling off the abrasive transporting hose from the nozzle end instead of by shutting down the abrasive valve.
2) Dial indicator measuring method could collect cutting front information accurately.
3) The observations in the paper confirmed that the profiles of the cutting front are real parabolic curves. Therefore, using a parabolic curve to fit the AWJ cutting front is good enough. And this is important for AWJ cutting model building in the future.

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