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ORIGINAL ARTICLE

A key parameter to characterize the kerf profile error generated by abrasive water-jet

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Abstract As the only cold high-energy beam machining technology, abrasive water-jet (AWJ) is one of the most rapidly developed techniques in material manufacturing industry. However, the application of AWJ is limited by the cutting accuracy it can achieve. Kerf profile generated by AWJ is different as the cutting parameters change. As a result, it has become a major factor which affects the cutting accuracy when AWJ is used as a machining tool. Researchers used taper error to characterize kerf profile error generated by AWJ in the past years. And many efforts have been put on how to eliminate taper error by using a tilting cutting head of a 5-axis AWJ machine. However, using taper error to characterize the kerf profile error generated by AWJ is not accurate since kerf profile error might appear in different styles. And using a 5-axis AWJ machine to eliminate taper error is only effective in some special cases. To effectively eliminate taper error, the first thing needs to do is to find out whether the kerf profile error can be compensated or not. Based on research, a key parameter, named kerf profile coefficient Ω, which can be used to characterize kerf profile error and further to guide people to use different ways to compensate kerf profile error, has been defined in this paper. To further illustrate the efficiency of this coefficient, a series of cutting experiments have been carried out and the experimental results have been discussed.

Keywords Abrasive water-jet · Precision cutting · Kerf profile error · Kerf profile coefficient

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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 paperboard, sponge, etc. 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, AWJ has been used extensively in industry currently. Now, parts with tolerance less than 0.1 mm can be cut by AWJ directly. However, the further application of this technology has been limited

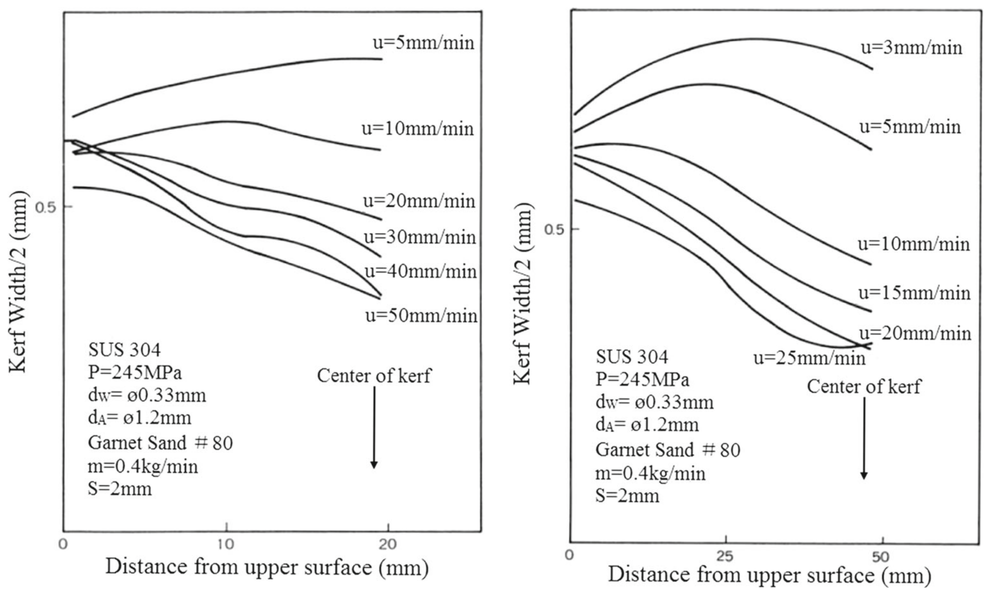

Fig. 1 Kerf profiles in AWJ cutting [1]

by its cutting accuracy. Unlike those traditional manufacturing methods, in which the kerf profile is a fixed one which matches to the shape of the tool, AWJ's kerf profile changes when any cutting parameter changes. Many researchers put lots of effort to investigate AWJ's kerf profile. As early as 1990, Matsui et al. demonstrated that the kerf profile is a function of cutting speed [1]. According to Matsui et al., the kerf profile curvature changes from convex to concave as the cutting speed decreases, the results he got are shown in Fig. 1. In 2009, Zeng et al. reported that the kerf profile is convex in thin workpiece and concave in thick workpiece [2]. As a result, AWJ's kerf profiles might appear in different styles. Some of them appear as a positive trapezoid on cross section, and some of them appear as an inverted trapezoid. Others appear as a barrel on cross section, etc., as shown in Fig. 2 [3]. As any of the cutting parameters change, the kerf profile might change in appearance. Therefore, it's a big challenge to get accurate kerf profile by using AWJ as a cutting tool.

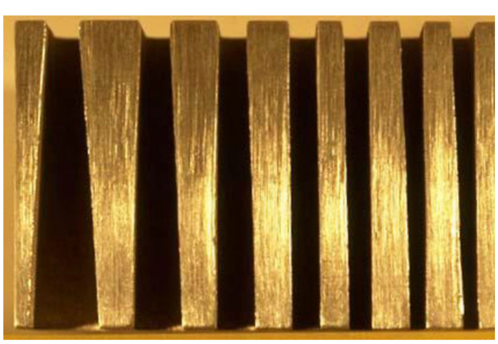

Fig. 2 Kerf profile changes as AWJ cutting conditions change [3] (Cutting speed increases from left to right)

To get precision cutting, some other researchers used taper error to characterize kerf profile generated by AWJ. Taper error was defined as half of the difference between the top and bottom kerf width. Taper angle was defined as the arctangent of taper error over thickness. In 2007, Hashish reported that taper increases with the increasing of the cutting speed [4]. In 2008, Maccarini et al. revealed that the taper increases with the increasing of the hardness of the workpiece [5]. Furthermore, many researchers have investigated the taper of different materials machined by AWJ and revealed the relations between taper and cutting parameters, such as cutting speed, water pressure, etc. [6–9]. Except that, some researchers tried to use mathematical models to characterize taper error. In 1992, Chung et al. derived a linear regression equation which showed that the taper is related to mixing tube diameter, abrasive flow rate, stand-off distance, etc. [10]. Also in 1998, Groppetti et al. assumed that the input energy is dissipated along the thickness, and then he derived a mathematical model of taper [11]. In 2000, Annoni et al. derived a relatively simple taper model based on the analysis of a multiple linear regression [12].

After knowing the factors which affect taper, a method, which could eliminate taper error, has been proposed and applied in AWJ cutting process [4, 13]. In this method, a cutting head was tilted a small angle along the direction, which is perpendicular to the cutting head moving direction, to compensate taper error, as shown in Fig. 3. Since then, this method has been used extensively in industry to eliminate taper error.

However, not each taper error can be eliminated by using the above method because the kerf profile might present in different styles under different cutting conditions. In order to identify whether the taper error could be eliminated or

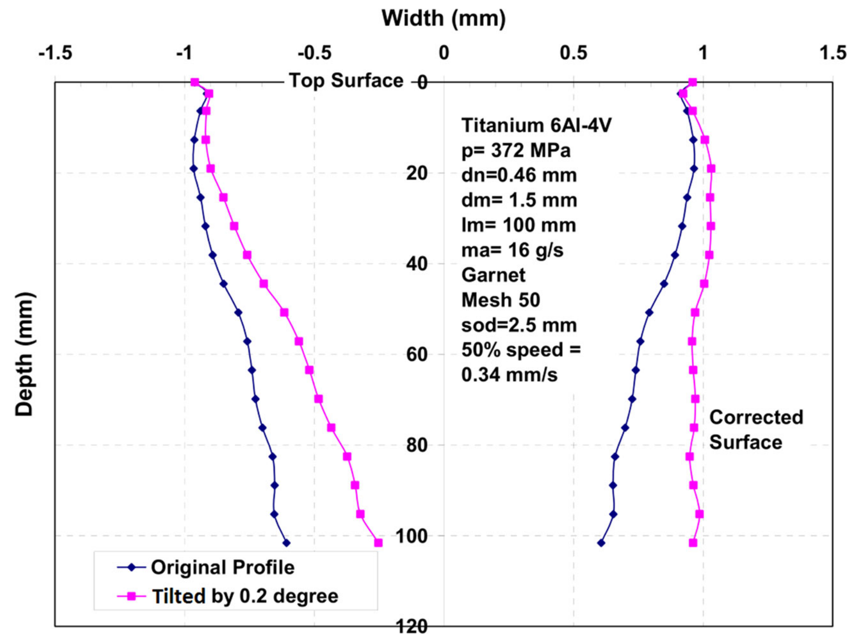

Fig. 3 Reduced surface taper by angular compensation [4]

not, a key parameter, named kerf profile coefficient, has been searched out in this paper.

2 Experimental investigation on kerf profile

Previous researchers have demonstrated that kerf profile is affected by cutting conditions. To find out how each cutting parameter affects kerf profile in detail, a series of experiments have been carried out in this paper.

2.1 Experimental design

Without a doubt, many parameters, which include water pressure, abrasive flow rate, abrasive type, abrasive mesh, orifice diameter, mixing tube diameter, target material type, target material thickness, cutting speed, etc. would affect AWJ cutting process [14]. Research on how each parameter affects kerf profile is very complicated since too many parameters are involved. To simplify the experimental process, the values of several parameters have been fixed. For example, garnet has been selected as the abrasive type and 100 mesh size of abrasive particles has been used in this experiment. Though abrasive type and mesh size would definitely affect AWJ cutting process, and further might affect kerf profile, it is reasonable and feasible to fix the values of these two parameters since more than 95 % of AWJ cutting process is finished with garnet and 100 mesh is the regular particle size used. Except that, aluminum 6061T is selected as target material since this type of material is used widely in industry. Further, a nozzle combination, 0.33 mm as the orifice diameter and 0.89 mm as the mixing tube diameter, has been used in this experiment. Other parameters, such as abrasive flow rate, water pressure, cutting speed, and target material thickness, etc., have been investigated in detail. To investigate each of those parameters, which have been listed in Table 1, different levels have been tested in this experiment. In Table 1, Q3 and Q5 are named as cutting surface quality number, and they represent different cutting speed levels. The relationship between cutting surface quality number and cutting speed is obtained from the model of Zeng [15] as shown in following:

$$u = \left(\frac{N_m P_w^{1.25} \dot{m}_w^{0.687} \dot{m}^{0.343}}{C_s q H D^{0.618}} \right)^{1.15} \quad (1)$$

where u represents cutting speed (mm/s); N_m represents the machinability number of material; $\dot{m}_w$ represents water flow rate (lpm); $\dot{m}$ represents abrasive flow rate (g/s); P_w represents water pressure (MPa); C_s represents scale factor;

Table 1 Experimental parameters

Cutting parameters	Specifications
Target material	Al6061-T6
Orifice diameter [mm]	0.33
Mixing tube diameter [mm]	0.889
Abrasive type	Garnet
Abrasive size [mesh]	100
Standoff distance [mm]	1.5
Abrasive flow rate [Kg/min]	0.35, 0.45
Water pressure [MPa]	245, 315, 385
Cutting speed level	Q3, Q5
Target material thickness [mm]	5, 10, 25, 50

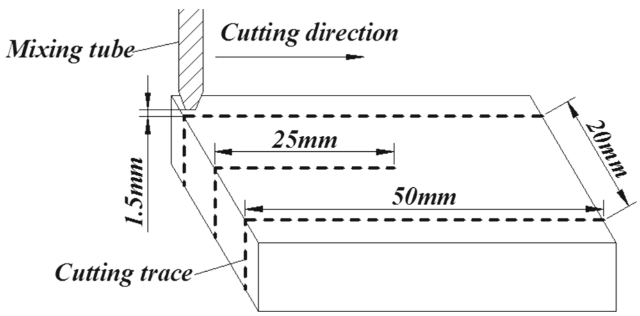

Fig. 4 Cutting path for each sample

q represents cutting speed level; D represents mixing tube diameter (mm); and H represents the thickness of sample (mm).

After the parameters are selected, samples with 20 mm wide and 50 mm long have been cut under each set of parameters. The reason for selecting a 50-mm-long sample is to get a stable phase traverse speed since the nozzle traverse process would cover the acceleration phase, stable speed phase, and deceleration phase. As we know, in acceleration phase and deceleration phase, the cutting speed is changing on each spot. By cutting a 50-mm-long sample, a stable phase traverse speed can be gotten. In order to get accurate kerf profile needed, the measurement should be carried out on those spots cut in stable speed phase. And for each sample, a 25-mm-long line in the middle of sample is also cut for each sample. This line cut could be ignored in this paper since it is for cutting front research purpose. The cutting path is showed in Fig. 4.

Fig. 5 Sylvac Dial Test Indicator 905.4321

Table 2 The typical parameters of the indicator

Measurement range	0.8 mm
Stylus length	12.5 mm
Resolution	0.001 mm
Maximum error	0.01 mm
Repeated error	0.003 mm
Repeatability	0.001 mm

2.2 Measurement procedure

Measurement is another action needs to be taken carefully in order to get accurate kerf profile information. It is not easy to get accurate kerf profile information by measuring the narrow kerf profile directly. In this paper, an indirect measurement method has been used. In this method, each side wall profile of the sample was measured respectively by a Sylvac electronic dial test indicator 905.4321 (As shown in Fig. 5). The typical parameters of this indicator are listed in Table 2. By a controlling system, the dial indicator can be moved along any direction needed. At the same time, the measurement results can be recorded accurately.

Before measurement starts, a calibration process is needed. The purpose of the calibration is to calibrate the cutting head and nozzle to be perpendicular to the work surface. The process is called squareness calibration by Zeng et al., which uses a 200 mm × 200 mm marble checking

Fig. 6 Squareness calibration tool used in experiment [16]

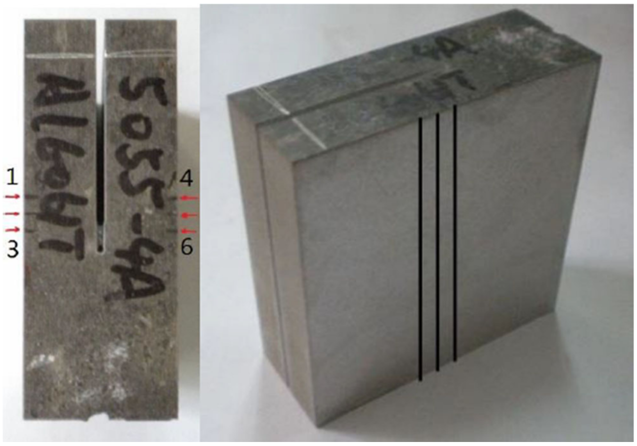

Fig. 7 Measurement of the kerf profile

platform and a dial indicator as shown in Fig. 6 [16]. The dial indicator was swung around to four different positions, and the measurement results are entered into the controlling system in the calibration process. Then the system would tilt the cutting head to be perpendicular to the work surface automatically. In this measurement, the marble was fixed on the work surface, and the specimen was positioned on the marble surface. A dial indicator was then used to measure the contour of the kerf profile at a series of equally spaced points along the marked lines shown in Fig. 7 to produce a series of the points which represent kerf profile. And for each side wall, three lines have been selected for

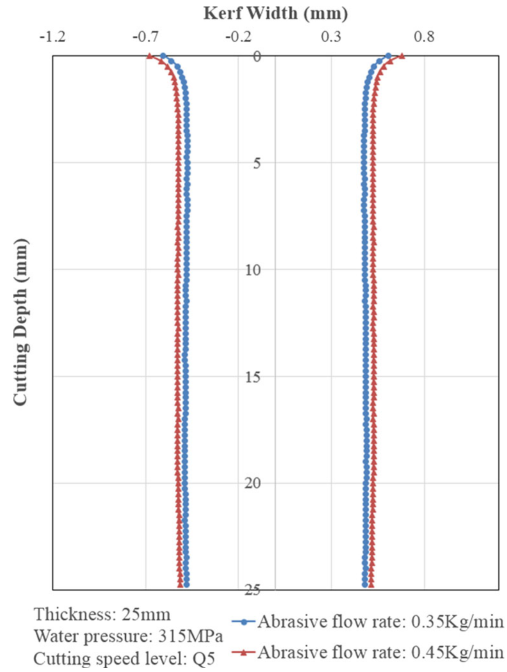

Fig. 9 Kerf profiles affected by abrasive flow rates

measurement purpose. Therefore, three sets of data of each single side have been obtained. Averaging these three sets of data, one curve of kerf profile on a single side has been obtained. Then averaging the two sets of averages of two sides, an accurate kerf profile can be gotten.

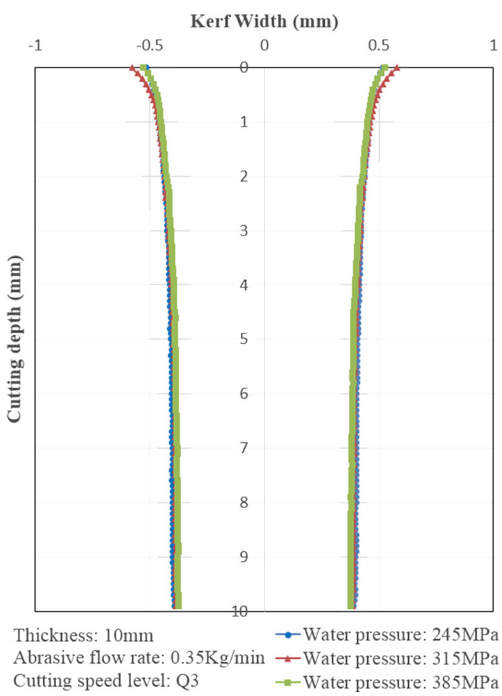

Fig. 8 Kerf profiles affected by water pressures

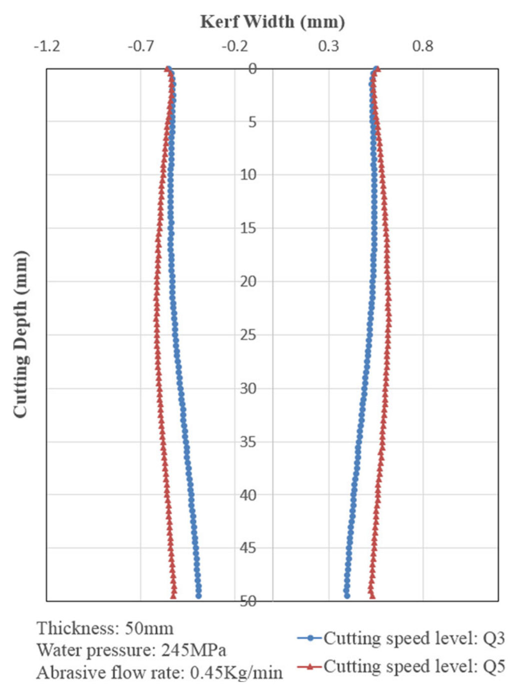

Fig. 10 Kerf profiles affected by cutting speeds

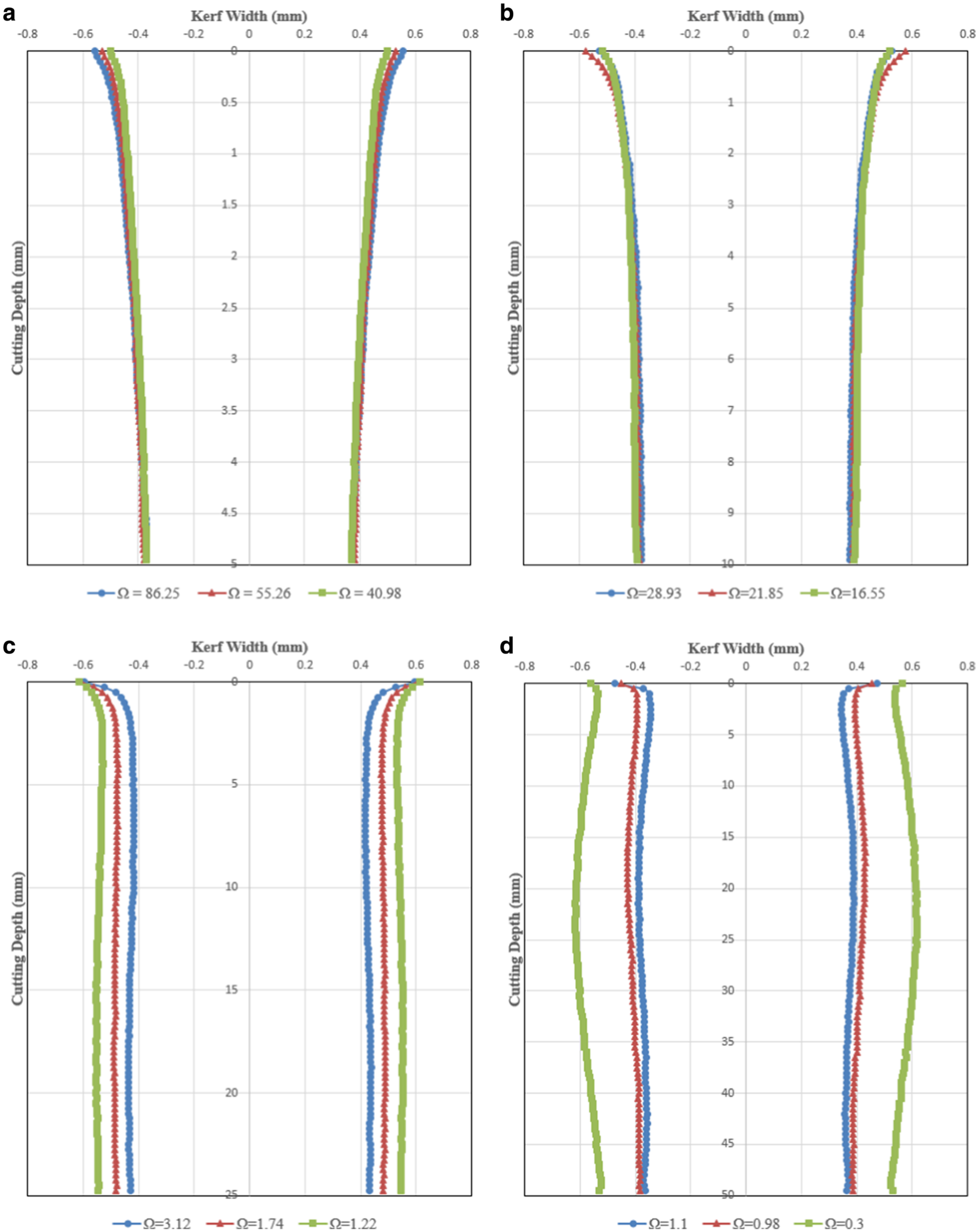

Fig. 11 **a–d** Kerf profiles under different kerf profile coefficients Ω

3 Sample analysis

The kerf profile of sample cut by AWJ under different cutting parameters is shown in Figs. 8, 9 and 10. As shown in those figures, there is a small round corner at the top edges owing to the erosion by loose particles [17]. Removal of the small round corner, the kerf profile can be categorized into three styles, including convex shape, straight shape, and concave shape, as shown in Figs. 8, 9 and 10, respectively. So, using taper error to describe kerf profile is not accurate enough. And by tilting a small angle to compensate taper error is only effective when kerf profile shape is convex or straight. Therefore, to effectively compensate taper error, the first thing needs to do is to find out kerf profile style under different cutting parameters.

If the thickness of the target material is fixed, as the cutting speed decreases, the kerf profile shape would change from convex to concave. This has been demonstrated by previous researchers and also been verified in this paper. Therefore, it is reasonable to deduce that the cutting speed is positively correlated to kerf profile. As mentioned above, cutting speed is decided by many parameters, which include water pressure, abrasive flow rate, nozzle combination, etc. So, without a doubt, kerf profile is related to those parameters too. For the same target material, as the cutting speed is fixed, when the thickness of the target material increases, the kerf profile might change from concave to convex. So, it is also reasonable to deduce that the kerf profile is negatively related to the thickness of the target material.

Based on the analysis of the experimental data, a kerf profile parameter, named kerf profile coefficient, has been researched to determine the curvature of kerf profile. This coefficient is shown in following,

$$\Omega = \frac{u}{H} \tag{2}$$

Where Ω is the kerf profile coefficient; u is the cutting speed (mm/min); H is the thickness of workpiece (mm).

Different kerf profile coefficients Ω correspond to different kerf profiles, which have been shown in Fig. 11. To further research the relationship between Ω and the kerf profile, a barrel error, named BE, is selected to describe the

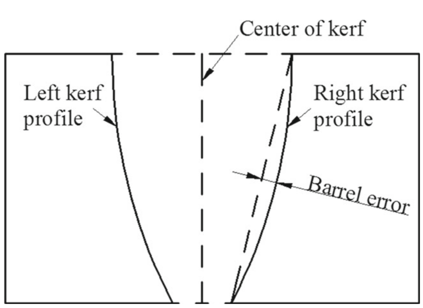

Fig. 12 Barrel error

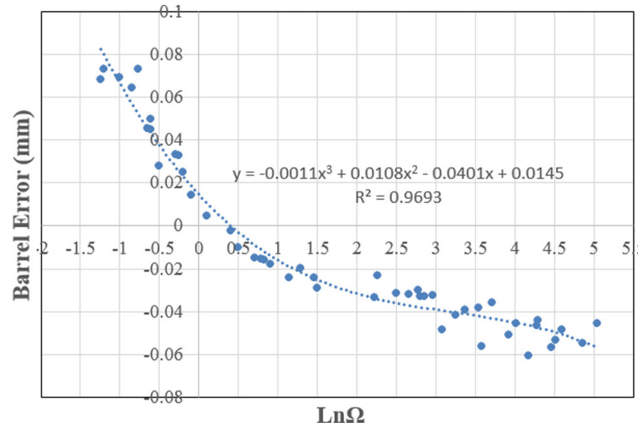

Fig. 13 Relation of barrel error vs. LnΩ

kerf profile curvature in this paper. As shown in Fig. 12, the value of the barrel error (BE) is the maximum deviation of the kerf profile from a base line connecting the top and bottom edges of the kerf profile [2]. This paper measured the barrel errors (BE) of 48 samples, and the relation between LnΩ and BE is shown in Fig. 13. Considering the measuring error and actual AWJ cutting surface condition, ±0.02 mm is selected as the gate value of BE, which is acceptable for most people. Therefore, when LnΩ values are between −0.13 and 1.18, the kerf profiles is with trapezoid shape or rectangular shape. And when the value of LnΩ is more than 1.18, the kerf profile is with convex shape. And when the value of LnΩ is less than −0.13, the kerf profile is with concave shape, as shown in Fig. 13.

To verify the above results, another series of experiments have been carried out. According to experiments, when the value of LnΩ is 0.4 (the corresponding value of Ω is 1.5), the value of BE is closed to zero. So, in this series of experiments, the value of LnΩ has been selected as 0.4. Based on the selected LnΩ, the cutting parameters have been listed in Table 3. And the kerf profiles are shown in Fig. 14. Need to note that, the round corner on each edge of the sample,

Table 3 List as Ω equal to 1.5

Parameters	Cutting speed [mm/min]	Target material thickness [mm]	Water pressure [MPa]	Abrasive flow rate [kg/min]
Test 1	15	10	385	0.344
Test 2	15	10	315	0.421
Test 3	15	10	315	0.227
Test 4	15	10	245	0.344
Test 5	37.5	25	385	0.195
Test 6	37.5	25	315	0.195
Test 7	37.5	25	315	0.421
Test 8	37.5	25	245	0.195

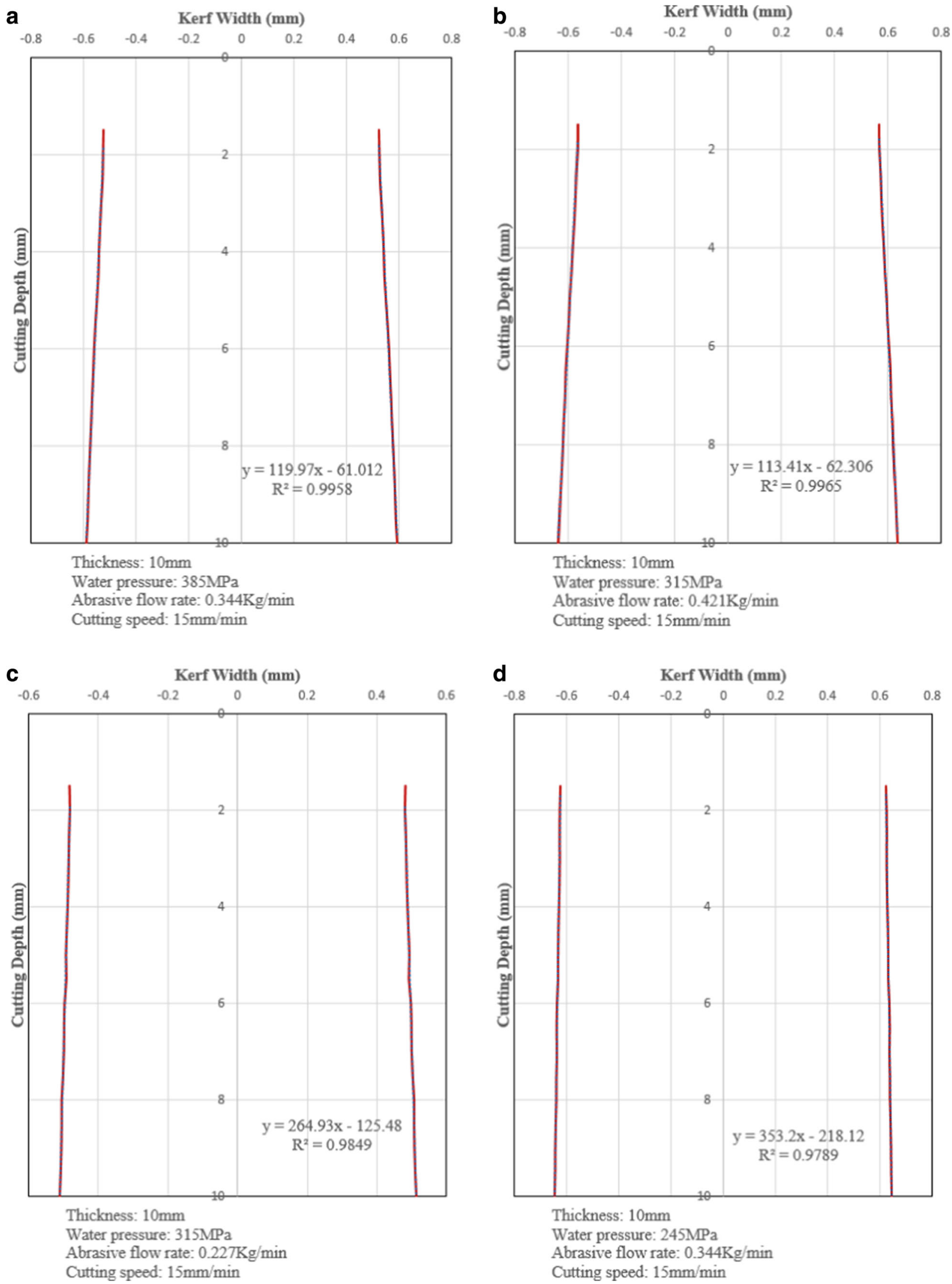

Fig. 14 **a–h** Kerf profiles as Ω is fixed as 1.5 under different cutting parameters

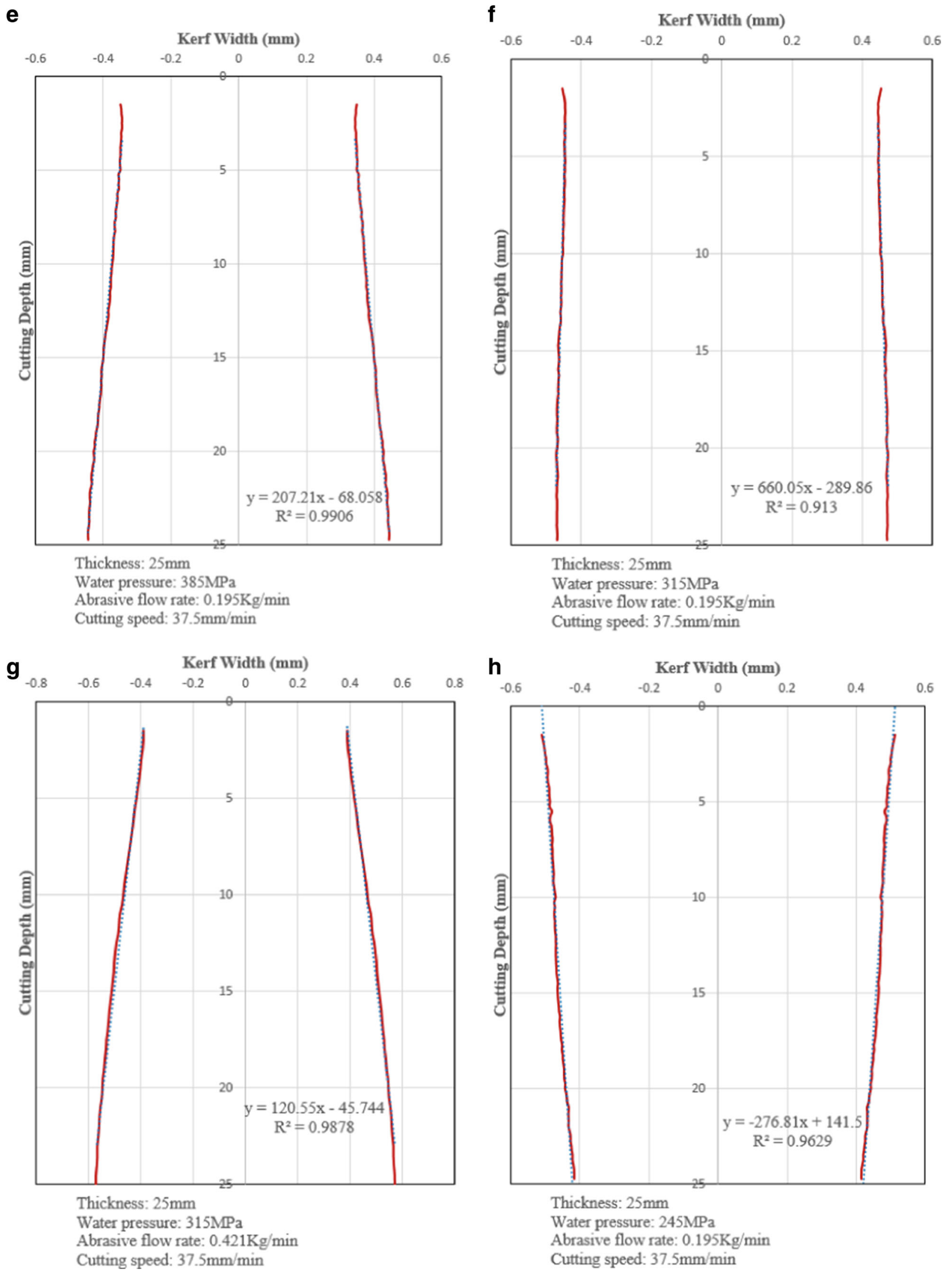

Fig. 14 (continued)

Table 4 The values of BE of samples

Test No.	BE [mm]
Test 1	−0.0044
Test 2	−0.0039
Test 3	−0.0045
Test 4	0.0020
Test 5	−0.0142
Test 6	−0.0115
Test 7	0.0192
Test 8	−0.0133

which is caused by erosion of loose abrasive particles, has been removed in all figures. The values of BE of samples have been listed in Table 4.

Figure 14 shows that, as LnΩ is equal to 0.4, the cross section of kerf profile can be characterized as a trapezoid. It means that the kerf profile can be characterized as taper error, which can be eliminated by tilting the cutting head a small angle in cutting process.

For some very thick samples, slowing down cutting speed is necessary to cut them. In that case, the value of LnΩ might be smaller than -0.13. It means that the value of kerf profile coefficient might be smaller than 0.88. That means it is impossible to correct the kerf profile error completely as the sample is too thick. So, finding out the thickest sample whose kerf profile error can be corrected completely is an effective way to characterize samples.

To find the thickest sample mentioned above, a separation speed needs to be calculated by using (1).

Combining (1) and (2), the kerf profile coefficient can be obtained as follows,

$$\Omega = \frac{60}{H^{2.15}}\left(\frac{N_m P_w^{1.25}\dot{m}_w^{0.687}\dot{m}^{0.343}}{C_s q D^{0.618}}\right)^{1.15} \quad (3)$$

If Ω =0.88, the thickness can be expressed as,

$$H = 7.13\left(\frac{N_m P_w^{1.25}\dot{m}_w^{0.687}\dot{m}^{0.343}}{C_s q D^{0.618}}\right)^{0.535} \quad (4)$$

Using the above equation, the maximum thick sample can be decided as the cutting condition is settled down.

4 Conclusions

Based on the discussions above, the following conclusions can be drawn:

1). Using taper error to characterize kerf profile error and further using a tilting cutting head to eliminate taper error is not feasible since kerf profile is changing as cutting conditions changes.

2). A kerf profile parameter, named kerf profile coefficient Ω, has been defined to determine the curvature of kerf profile. This coefficient provides a quick solution to predict whether the kerf profile can be eliminated or not.

3). The relationship between Ω and kerf profile curvature has been searched out and verified through a series of experiments.

4). Based on the kerf profile coefficient Ω, the maximum thickness of the sample whose kerf profile can be corrected has been found out.

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