A Study on Straightness of Deep Hole in Small-Diameter Drilling of Stainless Steel

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Abstract. This paper describes influence of the cutting conditions on the hole shape accuracy in deep-hole machining of stainless steel with small-diameter drill. The drilling tests were carried out by changing the step feed, the rotational speed and the feed rate in order to investigate the relationship between the straightness of the hole and the cutting conditions. As a result, it was found that the thrust force decreased with a decrease in the step feed amount and accordingly the straightness was improved. By changing the drill in incremental step from short drill length to long drill length, the straightness was improved.

Introduction

Pressure vessels used in large-scale facility such as an electric power plant is mainly fabricated by welding the thick stainless steel plates. As the residual stress is present in the welded portions, the stress needs to be measured to satisfy the safety criterion. For this measurement, DHD (Deep Hole Drilling) method is employed. A hole with a degree of diameter of 2mm and depth of 200mm is required in order to inspect the residual stress generated in the pressure vessel.

However, it is extremely difficult to drill hole with an aspect ratio (ratio of the hole depth to the tool diameter) of 100. With an increase in the aspect ratio, the chips become hard to be evacuated to the outside of hole and the higher cutting heat is generated at the cutting point. As a result, the shape accuracy of the hole is deteriorated and the tool life is shortened [1, 2]. Furthermore, in the deep-hole drilling with small diameter, the tool rigidity decreases and the high speed revolution is required comparing with the conventional aspect ratio. Thus, the buckling and the failure of the tool are easy to occur.

Authors successfully machined the hole with diameter of 2 mm and depth of 200mm through a trial and error process and the ingenious attempt such as the way of oil supply and step feed drilling [3]. However, a cause-and-effect relationship between the machining accuracy and the cutting conditions is not completely confirmed.

In this study, the drilling tests were carried out by changing the step feed, the rotational speed and the feed rate in order to investigate the relationship between the straightness of the hole and the cutting conditions. It is discussed how the cutting conditions for drilling small-diameter deep holes in stainless steel affect the straightness of the hole.

Experimental Method

The tapping center (TV-30, Mori Seiki Co., Ltd.) was employed for the drilling experiments. High-speed steel (HSS) and tungsten carbide drills were used for the deep-hole drilling. The work material is stainless steel (SUS304) which is commonly used for pressure vessels. The thrust force, the surface roughness and the straightness of the hole were measured. A three-component force transducer (9378B, Kistler) was used to measure the thrust force. Water-soluble cutting lubricant was applied on the surface of workpiece. The step feed drilling technique which is commonly performed in the deep-hole drilling was adopted.

Experimental Results and Discussion

Drilling of Hole with L/D=100. Authors have been investigating the appropriate cutting conditions for machining of the hole with diameter of 2mm and depth of 200mm [4]. Eventually, the targeted deep hole was successfully machined through a trial and error process and the ingenious attempt. Figure 1 shows a photograph of drilling method and the chips evacuated out of hole. The oil pool was fixed on the top side of workpiece and the drilling operation was performed in the oil to prevent air bubble from entering the hole. The chips were evacuated out of the pool through the outlet hole on the wall surface to prevent the chips from piling up.

Table 1 shows the cutting condition when the targeted hole was successfully machined. Two different tungsten carbide drills were used. Firstly, the pilot hole with depth of 6mm was drilled and then the hole with depth of 40 mm was drilled by another commercially available drill with flute

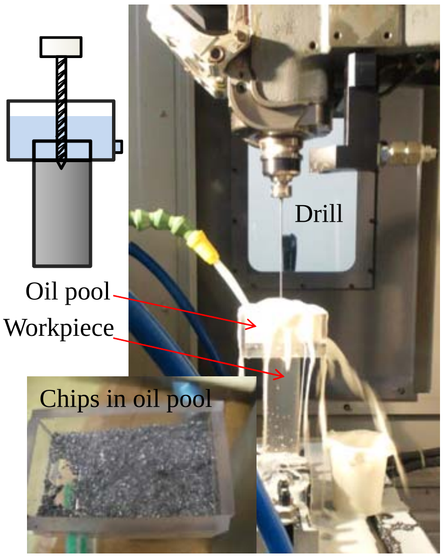

Fig. 1 Deep hole drilling method.

Table 1 Cutting conditions.

Hole depth	[mm]	0-40	40-200
Cutting speed	[m/min]	40	8
Feed rate	[mm/rev]	0.04	0.02
Step-feed	[mm]	0.01	0.01

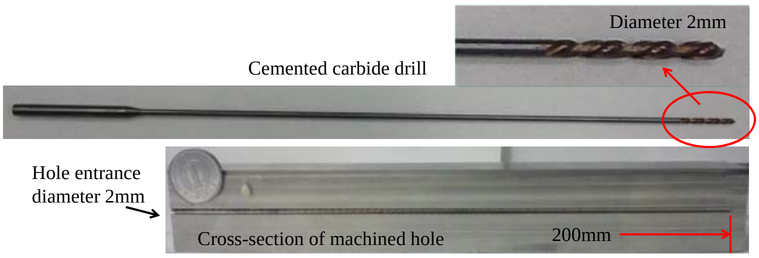

Fig. 2 Cross-section of deep hole and long drill used.

length of 50mm. After that, the drill was exchanged to specially designed drill with flute length of 205mm and the special long drill was penetrated to 200mm in depth with step feed of 0.01mm.

Figure 2 shows the specially designed long drill and the cross-section of the hole which was machined by the milling cutter. The cross section shape was measured by CCD laser displacement sensor and the straightness of the hole was evaluated based on the cross section shape measured at the position of 10mm interval from the hole entrance. Figure 3 shows the deflection of the hole obtained from the cross-section shape with reference to the hole entrance. The deflection increases with an increase in the hole depth, while the straightness is good in the range

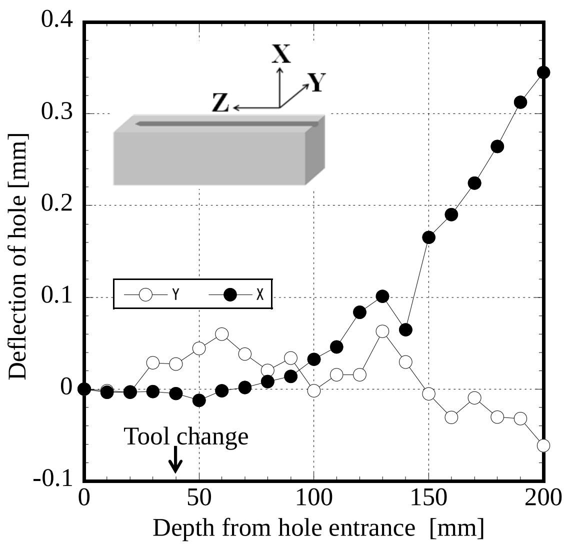

Fig. 3 Deep hole drilling method.

of 50mm or less in depth. After exchanging to the long drill, the deflection steeply grows. It is understood that the tool length has an influence on the hole deflection or the straightness.

As mentioned above, the hole with diameter of 2mm and depth of 200mm was successfully machined based on the knowledge obtained by the experiments and through a trial and error process. However, a cause-and-effect relationship between the machining accuracy and the cutting conditions is not completely confirmed. In the following section, the relationship between the thrust force and the step feed is examined and the effect of the cutting conditions on the straightness the hole is discussed.

Relationship between thrust force and step feed. A magnitude of thrust force was strongly responsible for the buckling and failure of tool in the drilling with small-diameter and long drills [4]. Then, authors have attempted to drill a long hole in the conditions of smaller feed rate and step feed than the conventional drilling conditions. Figure 4 shows the signal wave of the thrust force measured when drilling under the cutting conditions of spindle rotational speed 2400 min^{-1}, feed rate 0.02 mm/rev and step feed 0.01mm with high speed steel drill of diameter 2mm and flute length 50mm. Thrust force increases at the instant of the tool engagement in the workpiece and decreases at the back-feed of the tool. Stationary wave patterns are cycled in synchronization to the tool engagement and disengagement.

The relationship between the step feed and the thrust force is shown in Fig. 5. The cutting conditions are same as Fig.4. Values of the plots were obtained by the averaging procedure of the fluctuating values in the top of the signal wave. The thrust force drastically increases between 0.05mm and 0.05mm in the step feed. Notable change in the thrust force values is not seen in the range of 0.1mm or more and 0.01mm or less.

Figure 6 shows the signal wave of the thrust force measured when drilling without the step-feed technique under the same cutting conditions as Fig.4. The force values shown in Fig.5 are also superimposed in the continuous force signal of Fig. 6. The times corresponding to the horizontal axes of the graph were calculated based on the spindle rotational speed and the feed rate as the times required in the movement between the tool engagement and disengagement. In this cutting condition, it is understood from the continuous force signal wave that the time of approximately 0.1 second is required for a steady cutting process and the cutting process is in the unsteady cutting state till 0.1 second. Therefore, the magnitude of the step feed should be determined in consideration of the time for the unsteady cutting process, the spindle rotational speed and the feed rate.

Influence of step feed on hole straightness. It was mentioned in the previous section that the magnitude of the thrust force influenced on the buckling deformation and the failure of the tool. Then, the hole straightness is deteriorated with an increase in the hole depth. In this study, the hole straightness was evaluated as the amount of the hole curvature or deflection. As shown in Fig. 7, the

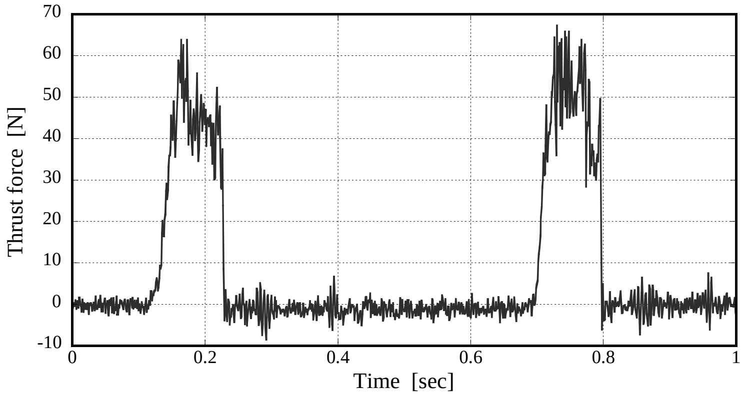

Fig. 4 Signal wave of thrust force in drilling with step feed.

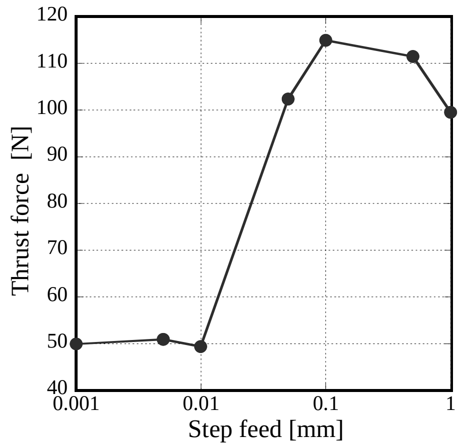

Fig. 5 Relationship between step feed and thrust force.

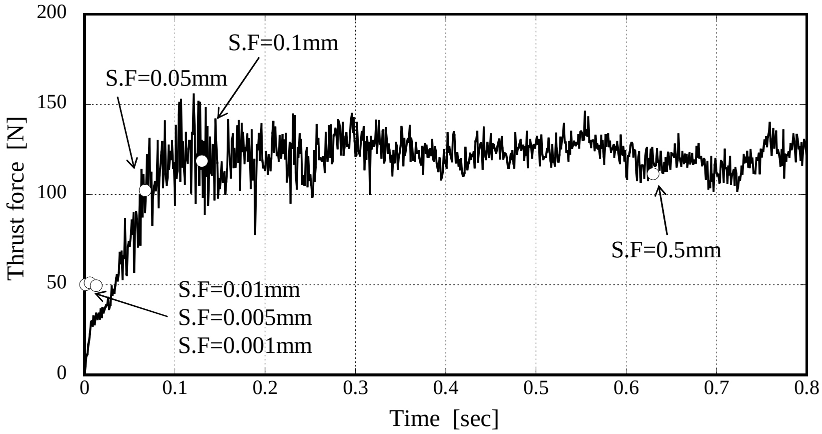

Fig. 6 Signal wave of thrust force in drilling without step feed.

workpiece was machined so that the cross section of the hole was visible. The cross section was measured by CCD laser displacement sensor and the reference point was fixed on the cross section at 10mm from the hole entrance. The displacement of the reference point at another cross section were defined as the deflections of X and Y directions. These measurement results were compared with the results measured by X-ray CT scanner and it was confirmed that both results were almost same.

Figure 8 shows the relationship between the deflection of hole and the depth from the hole entrance. The cutting conditions are spindle rotational speed 6000 min^{-1}, feed rate 0.02 mm/rev and step-feed 0.01mm with tungsten carbide drill (TiSiN coating) of diameter 2mm and flute length 70mm. Up to 0.06mm of deflection occurs at 60mm depth from the hole entrance. It is seen that the hole does not always curve in one direction. Then, in order to evaluate the magnitude of the deflection, we defined the accumulation of the deflection as shown in the shaded area of the graph. Figure 9 shows the relationship between the step feed and the accumulation of hole deflection. The accumulation of deflection increases with an increase in the step feed. Especially, the deflection rapidly

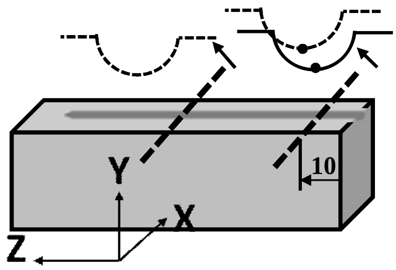

Fig. 7 Measurement of hole deflection by CCD laser displacement sensor.

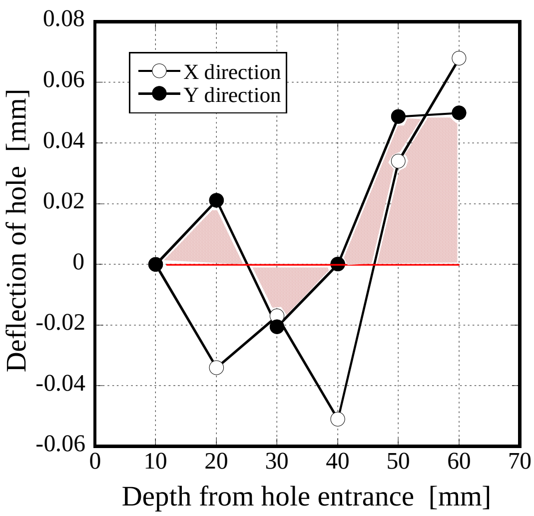

Fig. 8 Relationship between depth and deflection of hole.

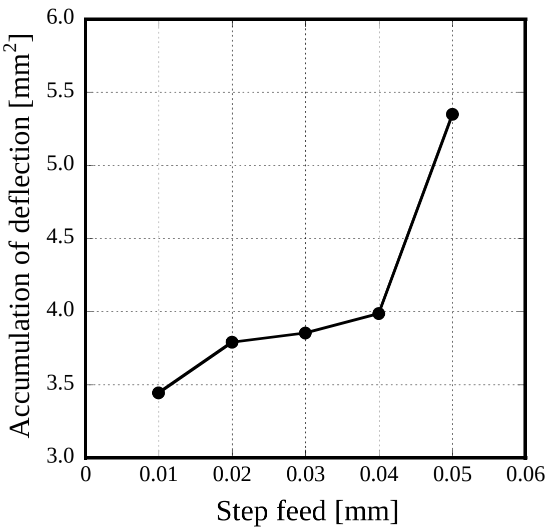

Fig. 9 Relationship between step feed and deflection hole.

increases in the condition of step feed 0.05mm and the best straightness is obtained in the case of step feed 0.01mm within this experimental condition.

Influence of tool length on hole straightness. In this section, an influence of the tool length on the thrust force and the hole straightness was examined. The drilling tests were carried out with three types of drills which have the flute length of 40mm, 50mm and 70mm. The rest of cutting conditions are the same as the experiments of the previous section. Figure 10 shows the changing process of the thrust force with and without the tool change. The dashed line indicates the thrust force change when the hole of 60mm depth was drilled by the drill of 70mm flute length without the tool change. The magnitude of the thrust force is approximately 100N and tends to increase in the depth of 40mm or more. The solid line indicates the thrust force change. Firstly, the hole of 30mm depth was drilled by the drill of 40mm flute length and the drill was changed to the drill of 50mm flute length. After drilling till 40mm depth, the drill was changed again to the drill of 70mm flute length and finally the hole of 60mm depth was drilled. The magnitude of the thrust force is approximately 85N in the case of using the short drill (40mm flute length), while the thrust force was approximately 100N in the case of using the long drill. By exchanging to the second drill and the third drill, the thrust force increased to approximately 95N and 110N, respectively. The accumulation of the deflection was 2.85mm^2 in the case of the tool change and 3.45mm^2 (see Fig. 9) without the tool change.

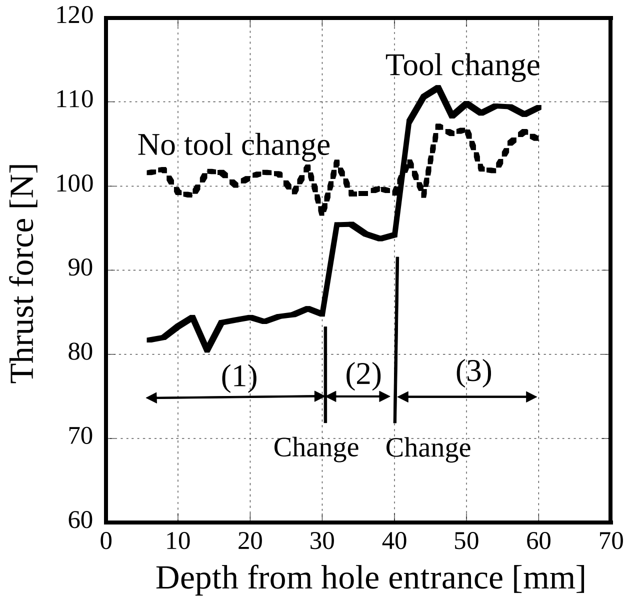

Fig. 10 Change of thrust force by tool length and tool change.

Influence of feed rate and spindle rotational speed on hole straightness. Figure 11 and 12 show the relationship between feed rate and thrust force, the relationship between spindle rotational speed and thrust force, respectively. The magnitude of the thrust force tends to increase with an increase in the feed rate and with a decrease in the spindle rotational speed, respectively. However, the thrust

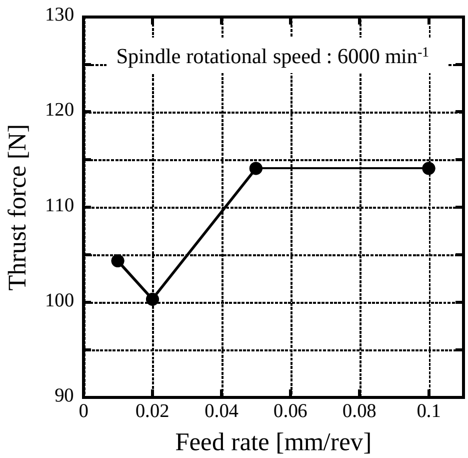

Fig. 11 Relationship between feed rate and thrust force.

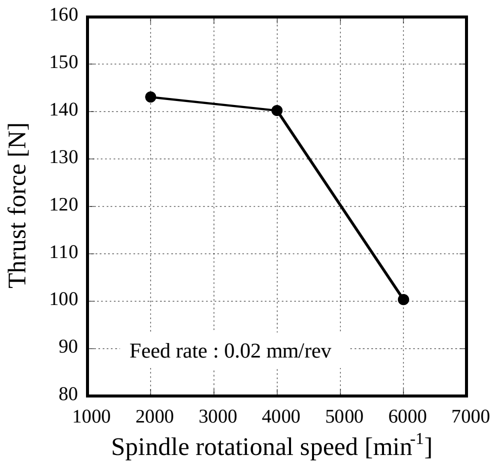

Fig. 12 Relationship between spindle rotational speed and thrust force.

force increases in the condition of feed rate 0.01mm/rev. Too small feed rate leads to a work hardening of the work material and a strong burnishing process due to small effective depth of cut. That results in the increase of the thrust force.

Figure 13 and 14 show the relationship between feed rate and the accumulation of the hole deflection, the relationship between spindle rotational speed and the accumulation of the hole deflection, respectively. These results correspond to the results of Fig. 11 and Fig. 12. It is understood that the magnitude or the change of the thrust force is totally responsible for the deflection of the hole or the hole straightness.

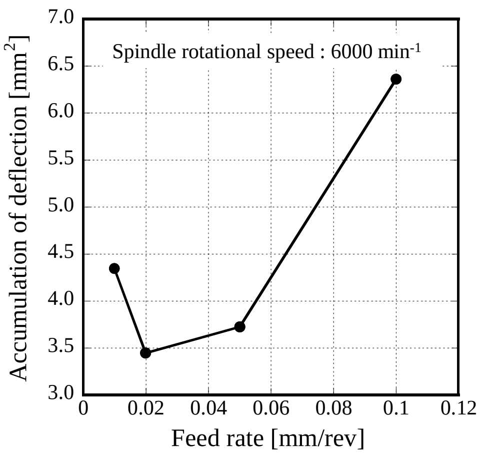

Fig. 13 Relationship between feed rate and accumulation of deflection.

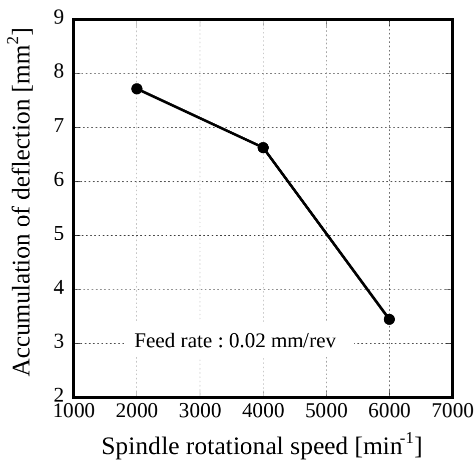

Fig. 14 Relationship between spindle rotational speed and accumulation of deflection.

Summary

The drilling tests were carried out by changing the step feed, the rotational speed and the feed rate in order to investigate the relationship between the straightness of the hole and the cutting conditions. The findings which were obtained from cutting tests are presented. It was found that the thrust force decreased with a decrease in the step-feed amount and accordingly the straightness was improved. By changing the drill in incremental step from short drill length to long drill length, the straightness was improved.

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