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Research on aviation aluminum alloy drilling technology for tube hydro-forming

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Abstract. Assembly connection quality directly influences service life of airplane in the manufacturing process of airplane. At present, the main airplane assembly connection method is mechanical connection, while most wear-out failures of airplane happen to the connecting drilling, thus service life of airplane can be improved after quality of the connecting drilling for aviation aluminium alloy material of tube hydro-forming is improved. In comparison with traditional manual drilling, automatic drilling can significantly improve drilling precision and drilling quality, which is more and more extensively used in aviation aluminum alloy manufacturing of tube hydro-forming. Requirements of automatic drilling for high efficiency, stability, and continuity are required to be satisfied in the automatic drilling process for aviation aluminum alloy manufacturing of tube hydro-forming. In addition, there are lots of complex conditions about disposable drilling on material lamination in the assembly process of airplane; it is hard to ensure drilling precision and drilling quality, thus lamination drilling mechanism has to be deeply researched and massive process experiments are required to be conducted so as to optimize drilling technology for ensuring drilling precision and quality.

Key words. Tube charging, Tube hydro-forming, Aluminium alloy drilling, Optimization of process parameter.

1. Introduction

Processing quality of the connecting hole is the foundation and key to ensure riveting quality in riveting assembly process of cabin for carrier rocket. Automatic drilling is one of effective methods to improve drilling quality and efficiency, but advantages and disadvantages of automatic drilling quality are mainly up to processing parameter. In case process selection is unreasonable, it is easy to lead to drilling burr, scratch, aperture and roundness tolerance, and other defects, which will influence riveting quality and structural assembly quality, thus drilling technology with

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high quality is the premise to obtain riveting components with high quality.

With the extensive use of automatic drilling equipment, in-depth research on automatic drilling process is conducted at home and abroad. Accessor method for pressing force of pressure foot to improve automatic drilling quality of robot is obtained in Literature [4] with the method finite element simulation. It is believed that bilateral pressing drilling can be used to restrain additional laminated clearance caused by flow stress so as to restrain burr travel after research on pressing form of laminated materials in automatic drilling process in Literature [5]. It is believed that lamination sequence and pressing force has the most significant influences on drilling quality after researching on automatic drilling parameter which influences lamination of titanium alloy and aluminium alloy in Literature [6]. It is believed that pressing force should be close to upper limit of tolerance zone for work-piece as much as possible after research on pressing force in the drilling process of helical milling in Literature [7]. Generation mechanism and control of automatic drilling burr is subject to in-depth research in Literature [8]. Speed of main shaft, feed rate, taper angle of tool, cooling type, and hole edge and burr formation law are researched in Literature [9]. Influences of robot foot pressure on automatic drilling of aluminium alloy are described in Literature [10]. Li Yuan, et al. have conducted researches on 191 pairs of drilling burrs under unilateral pressing force of aluminium alloy lamination, thus they believe that increase of pre-pressing force can significant restrain height of interlamination burr. Drilling parameter of automatic drilling and riveting for Boeing 737 end-piece panel is subject to in-depth research in Literature [11]. Ye Shunjian, et al. (4) have realized automatic drilling and riveting and have researched on process parameter of drilling in the cabin of carrier rocket booster.

It is know according to current literatures that automatic drilling has integrated influences of factors in several aspects. Product assembly, pressing force, tool parameter, machine tool parameter, cooling chip removal, and etc. have significant influences on drilling quality. In recent years, with extensive use of automatic equipment in the field of aerospace riveting assembly, based on increasing impendency for application of automatic drilling technology to cabin of carrier rocket, taking advantages of existing literature and research result, laminated panel for aviation aluminium alloy material of tube hydro-forming is taken as object to conduct automatic drilling process research and to research on influences of tool parameter, machine tool parameter, pressing force of lamination, and other factors on drilling quality in the thesis so as to obtain process parameter applicable to engineering application.

2. Experimental material and equipment

Test material is structural member for panel of aviation aluminum alloy material for tube hydro-forming, which is constituted by a skin and seven stringers. Stringer is distributed to external skin. Skin material is 2A12-T4 aluminium alloy with thickness of 1.2mm. Stringer material is 7A09-T6 with thickness of 3mm. Total thickness of drilling lamination is 4.2mm. The test sample is divided into two regions. Region I is used to test influences of automatic drilling parameter on drilling quality, while Region II is used to verify rationality of drilling parameter. The structure is shown in Fig. 1.

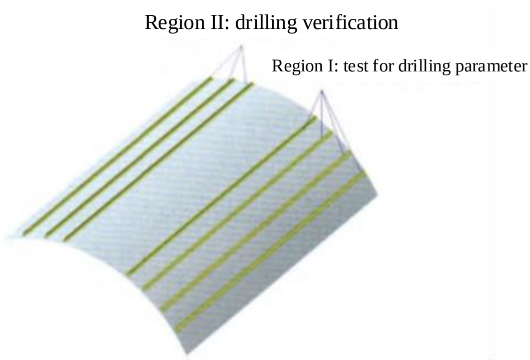


Fig. 1. Structural member of panel

Automatic drilling test for panel is conducted on automatic drilling and riveting machine on the panel of carrier rocket. As diameter and width of large-scale panel for rocket are large, rivet should be used to make temporary position for stringer and skin before installation of panel so as to ensure accuracy of stringer position distributed on the panel. Clearance between temporary fasteners is 300mm; half-round head rivet is used for position and connection. Each stringer should be divided into 7 segments so as to conduct drilling test. In order to avoid influences of the rest parameters on automatic drilling quality, vortex cooling pipe is used to conduct continuous cooling for the drill; strong suction device is used to remove drilling cuttings. Inspection of automatic drilling quality mainly includes roundness, perpendicularity, quality of hole wall, residual stress, positional accuracy, interlamination burr, exit burr, and etc. In terms of riveting and drilling of rocket panel, redundancy prevention and control is an important control item so as to prevent short circuit of instrument and equipment. Therefore, interlamination burr and exit burr are inspected in the test; burr height is measured with VML250 optical image measuring instrument, which is considered as evaluation indicator for measurement of automatic drilling quality. Pressing force, tool parameter, speed of main shaft, feed rate, and etc, in automatic drilling process are important parameters for drilling quality; in addition, pressing force is the most important parameter that influences height of lamination burr. Process researches are mainly conducted for this in follow-up test so as to obtain the optimal parameter for automatic drilling which is applicable to rocket panel. Firstly, aiming at drilling exit burr, research is conducted in the test; orthogonal experiment is used to analyze influence rule of speed of main shaft, feed rate, and sharp edge of tool on height of exit burr so as to select optimal drilling parameter. Then, drilling test under different pressing forces are conducted under the constant drilling parameter so as to research on influences of pressing force on height of lamination burr. Automatic drilling process is shown in Fig. 2.

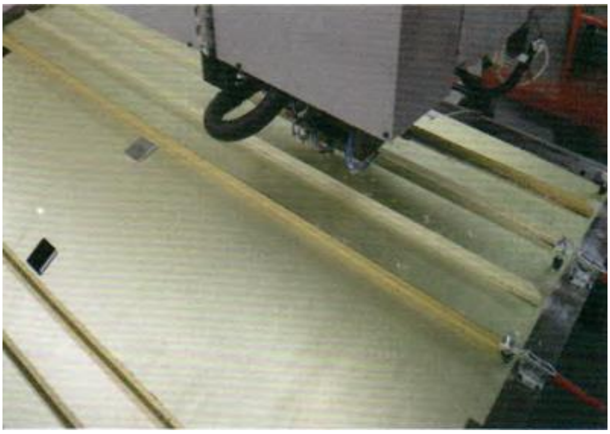


Fig. 2. Automatic drilling process

3. Selection of process parameter

Aviation aluminum alloy material for tube hydro-forming is applicable to high rotation speed and low feed rate, while aluminum alloy is applicable to moderate rotating speed and moderate feed rate. In case lamination of two materials is subject to a disposable drilling with the same process parameter, the four kinds of process parameters which can be selected are as follows:

1) High rotation speed and low feed rate contribute to improving drilling quality of aviation aluminum alloy material for tube hydro-forming. However, low-speed processing aluminum alloy has entangled filings, thus peck drilling is required to be considered at the time of automatic drilling. Meanwhile, high temperature under high rotation speed may lead to quick wear of tools, thus service life of tools will be reduced.

2) Drilling quality of aviation aluminum alloy material for tube hydro-forming with high rotation speed and moderate feed rate is worse than that with low feed rate. However, aluminum alloy has no entangled filings. Moderate feed will lead to quick wear of tool for aviation aluminum alloy material of tube hydro-forming; moreover, high rotation speed has influences on tool wear, thus tools are worn under the process parameter within the shortest time.

3) Moderate rotation speed and low feed can simultaneously ensure drilling quality of aviation aluminum alloy material of tube hydro-forming and aluminum alloy. Wear speed of tools is slow, which is easy to lead to entangled filings of aluminum alloy, thus it should be improved through peck drilling.

4) Tools for aviation aluminum alloy material of tube hydro-forming with moderate rotation speed and moderate feed is quickly worn. It is shown in above-mentioned analysis that lamination of aviation aluminum alloy material for tube hydro-forming should be subject to drilling with the same process parameter; moderate rotation speed and small feed rate are equilibrium point to select better process parameter, which can take into consideration of both drilling precision and drilling quality of

aviation aluminum alloy material for tube hydro-forming and aluminum alloy and can ensure that tools have better durability.

3.1. Drilling precision and drilling quality evaluation

Evaluation of drilling precision and drilling quality is an important content to research on drilling process of lamination for aviation aluminum alloy material of tube hydro-forming. Evaluation parameters for drilling precision and drilling quality of lamination for aviation aluminum alloy material of tube hydro-forming are shown in Fig. 3. Burr refers to drilling defect of aluminium alloy drilling; de-lamination, de-lamination, tearing, and burr are drilling defects at the time of drilling for composite materials. Fig. 4 is schematic diagram for evaluation of drilling precision and drilling quality for lamination of aviation aluminum alloy material for tube hydro-forming.

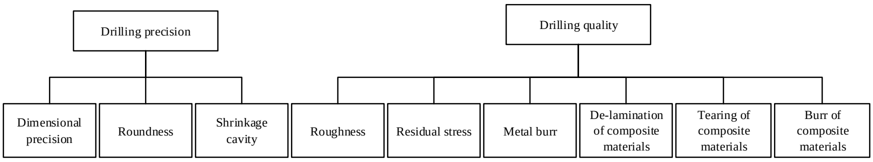


Fig. 3. Evaluation of drilling precision and drilling quality for lamination of aviation aluminum alloy material for tube hydro-forming

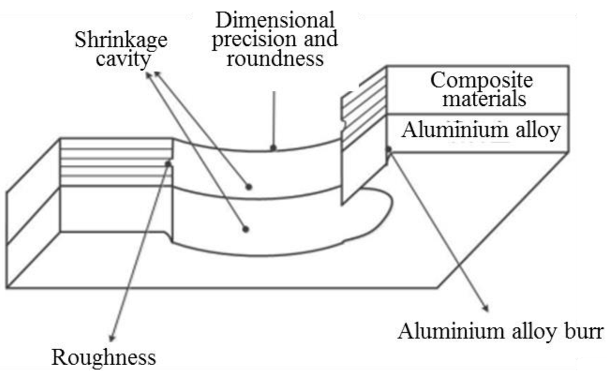


Fig. 4. Evaluation parameters for drilling precision and drilling quality of lamination for aviation aluminum alloy material of tube hydro-forming

Drilling precision mainly refers to dimensional precision and roundness of hole. Due to poor thermal conductivity of aviation aluminum alloy material for tube hydro-forming, surrounding area about the hole is subject to serious thermal expansion at the time of drilling, which will lead to shrinkage cavity after cooling. However, aluminium alloy does not have such phenomenon. Aperture difference value of the two materials can be considered as shrinkage cavity value for aviation aluminum alloy material of tube hydro-forming at the time of drilling. In addition to dimensional precision and roundness, shrinkage cavity value can be considered as an important parameter to evaluate drilling precision for lamination of aviation aluminum alloy material for tube hydro-forming.

In addition to roughness and residual stress, evaluation of drilling quality should include drilling defects of materials. Common drilling defects for aviation aluminum alloy material of tube hydro-forming are de-lamination, tearing, and burr, while common drilling defect for aluminum alloy is burr. In order to reduce de-lamination and tearing defects of aviation aluminum alloy material for tube hydro-forming, aviation aluminum alloy material for tube hydro-forming usually is placed in the upper layer, while the aluminum alloy is placed in the lower layer. In comparison with single-layer drilling of aviation aluminum alloy material for tube hydro-forming, common drilling defects, such as de-lamination, burr, and tearing of aviation aluminum alloy material for tube hydro-forming is reduced due to lower layer support in the drilling process of aviation aluminum alloy material for tube hydro-forming. In addition to roughness of the two materials, de-lamination, tearing, burr of aviation aluminum alloy material for tube hydro-forming and exit burr of aluminum alloy should be considered as parameter to evaluate drilling quality of lamination for aviation aluminum alloy material of tube hydro-forming.

3.2. Process optimization method

It is shown in drilling feature analysis of aviation aluminum alloy material for tube hydro-forming that drilling mechanism of lamination for aviation aluminum alloy material of tube hydro-forming is complex. Tools, wear, process, parameter, and influences in other aspects should be comprehensively considered in the process of engineering application. Fig. 5 is about research route of drilling process aiming at aviation aluminum alloy material of tube hydro-forming for new tools. Research method of the test is mainly based on the following thoughts: 1) research on unusable mechanism of process parameter; 2) single factor variable test to eliminate interference; 3) ensure basis of drilling reliability so as to research on tool wear and to take into consideration of economical efficiency.

Process parameter includes rotating speed and feed rate. The same process parameter is used to process the two materials. In case drilling precision and drilling quality are seriously inconsistent with requirements or tools are subject to failure and severe wear in the process of processing several holes, the process parameter shall be considered as being unusable. Process parameter which is unusable has two different expression forms. One is that drilling precision and drilling quality can not satisfy requirements; the other one is that severe tool wear, tipping, tool breaking, and etc. Unusable mechanism of process parameter is under the comprehensive influences of tools, material category and thickness, lamination mode, machine tool rigidity, and other factors, thus selection range of process parameter can only aim at specific working conditions. Selection of usable process parameter is the basis to formulate process parameter for further optimization test. Process parameter of follow-up test shall be selected within obtained range of process parameter according to certain way.

Drilling precision and drilling quality are different under different tool wear con-

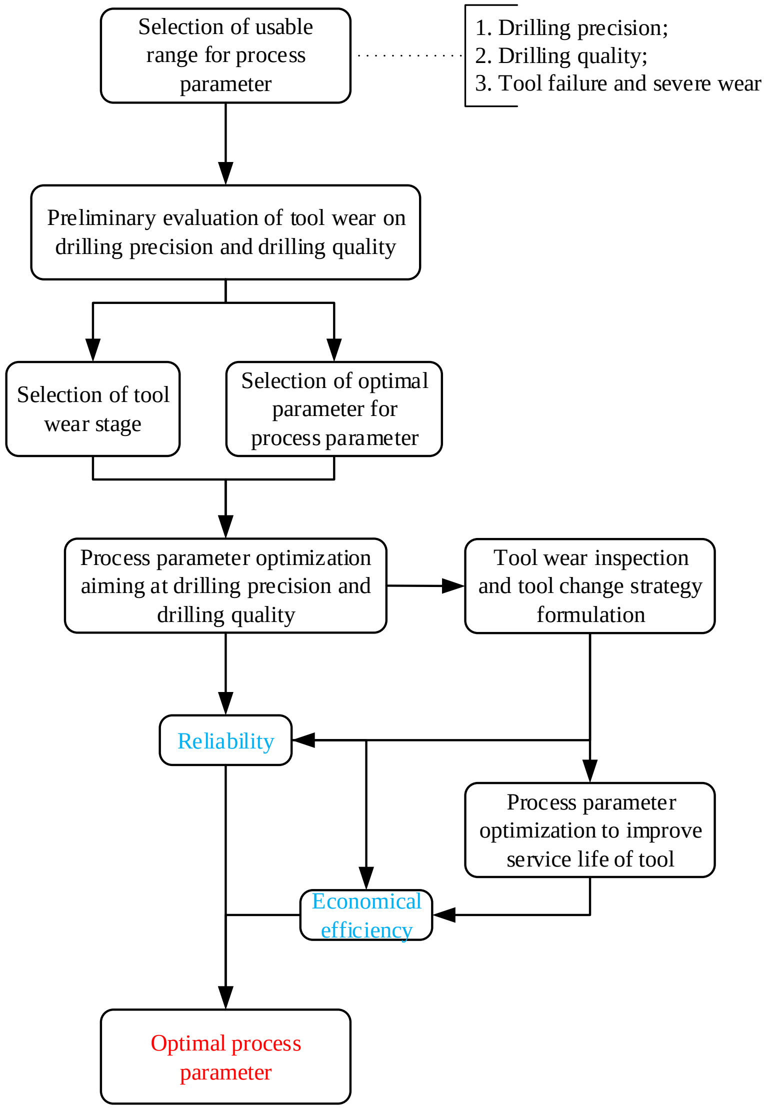


Fig. 5. Optimization path for drilling process parameter of lamination for aviation aluminum alloy material of tube hydro-forming

ditions. Single factor variable test for process parameter shall be firstly conducted so as to eliminate interference of tool wear in the process of process optimization for improvement of drilling precision and drilling quality. In consideration of drilling consistency and test costs, it is impossible to change a tool after processing several holes so as to conduct the test, thus the tool in a small wear influence stage on drilling precision and drilling quality should be selected so as to conduct test. Requirements for drilling precision and drilling quality should be ensured; optimized process parameter is required to be used; tools are required to be immediately changed, which are believed to ensure drilling reliability and to improve fatigue life of connecting parts. There is a margin for tool change; large margin may lead to tool waste when tools are changed with good processing performance, thus formulation of tool change strategy should ensure drilling precision and drilling quality and should take into consideration of economical efficiency for tools. Further optimization should be ensured for the purpose of improving service life of tool within process parameter range for drilling precision and drilling quality; the optimal process parameter to improve service life of tool should be selected so as to further improve economical efficiency of tool use.

4. Process parameter optimization to improve drilling precision and drilling quality

4.1. Test design

Lamination of aviation aluminum alloy material for tube hydro-forming with rotating speed of 3500rpm and feed rate of 0.05mm/r should be processed. Aviation aluminum alloy material for tube hydro-forming is CCF300 with the thickness of 3.2mm, while aluminum alloy is 7075 with the thickness of 3.1mm. Service life of the two drills should be evaluated. Tricuspid drill can be used to process about 600 holes, while twist drill can be used to process about 800 holes. Aperture and roughness of the first 100 processed holes should be inspected with small change. There is no obvious tearing which can be observed with naked eyes at the exit of aviation aluminum alloy material for tube hydro-forming; exit burr of aluminum alloy which is observed with naked eyes is small. New tools for the two tools are preliminarily selected and used so as to improve process parameter optimization for the purpose of drilling precision and drilling quality according to above-mentioned conditions. 5 levels of feed rate and rotating speed are selected so as to conduct 25 groups of tests in total. Each group should be conducted for three times; 75 holes should be processed in total, thus influences of tool wear on drilling precision and drilling quality can be controlled within certain range.

In case rotating speed of tricuspid drill is 3500rpm, $fmax$=0.1mm/r; in case feed rate is 0.05mm/r, $nmax$=7200rpm in above-mentioned test for selection of usable process parameter. In consideration of severe wear or tipping of tool which can be caused by interaction under high rotation speed and high feed rate, process parameter which is shown in Table 1 is selected to conduct test. In order to compare twist drill and tricuspid drill, the same process parameter as that of the tricuspid drill is selected to make process optimization for twist drill.

Table 1. Table for selection level of process optimization parameter

Parameter	Value				
Rotating speed (rpm)	2700	3500	4300	5100	5900
(mm/r) Feed rate (mm/r)	0.03	0.04	0.05	0.06	0.07

Aperture, roughness, height of exit burr for aluminium alloy, and axial force of each hole under 25 kinds of process parameter should be subject to inspection; in addition, mean value of measurement value for three holes should be taken. Quadratic regression model is used at the time of analysis:

$$X=C_0+C_1n+C_2n^2+C_3f+C_4f^2+C_5nf\,. \tag{1}$$

Where n indicates rotating speed with the unit of rpm; f indicates feed rate with the unit of mm/r; C_0—C_5 indicates undetermined constant value; X indicates optimized object, which is one of aperture, roughness, height of exit burr for aluminium alloy, and axial force.

Dimensional precision is an important basis to judge drilling precision basis, which is required to reach H8 dimensional precision grade in the fourth generation machine assembly. In terms of hole of Φ5, its upper deviation is required to be smaller than or be equal to 18μm with lower deviation being larger than or being equal to 0. Aperture of each hole should be measured through inside micrometer. In order to find variation law of aperture with process parameter, data point of discrete process parameter is subject to quadric surface fitting. In case empirical process determination coefficient R^2 obtained through fitting approximates to 1, qualitative or quantitative analysis of aperture variation with process parameter for three-dimensional surface diagram can be obtained through fitting.

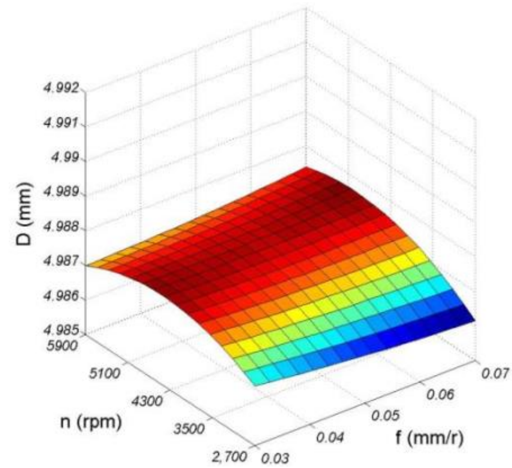
4.2. Tricuspid drill

It is shown in aperture variation with process parameter for aviation aluminum alloy material of tube hydro-forming that determination coefficient of formula which is obtained through aperture fitting of aviation aluminum alloy material for tube hydro-forming is small, because volatility of aviation aluminum alloy material for tube hydro-forming is small, which is only 0.002mm, thus test result is subject to restriction of inspection precision.

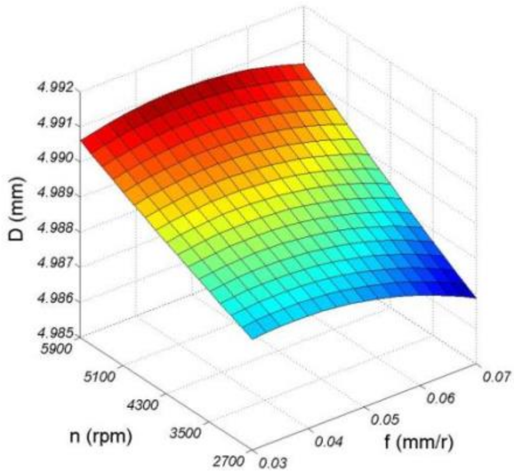
Three-dimensional surface diagram (Fig. 6) should be drawn in matlab for obtained fitting formula, which indicates that there is no obvious aperture variation with process parameter for aviation aluminum alloy material for tube hydro-forming processed with tricuspid drill. Moreover, aperture of aluminium alloy is slightly increased with increase of rotating speed. There is no obvious variation law for aluminium alloy aperture with feed rate. It is shown in comparison of the two diagrams that apertures of aviation aluminum alloy material for tube hydro-forming after being processed with tricuspid drill are smaller than aperture of aluminum alloy under different process parameters. In addition, there is obvious shrinkage cavity phenomenon for aviation aluminum alloy material for tube hydro-forming.

4.3. Roughness of aluminium alloy hole

It is found through roughness variation with process parameter of aviation aluminum alloy material for tube hydro-forming processed with tricuspid drill that determination coefficients of two fitting formulas are low, especially that of tricuspid



(a) CFRP



(b) Al

Fig. 6. Aperture under different process parameters

drill. In terms of tricuspid drill, roughness volatility detected in three holes under the same process parameter is large. The maximum measurement data can be 1.495μm, while the minimum value is only 0.268μm, because there is unknown adhesion burr (Fig. 7) when aluminium alloy approaches the entrance of aviation aluminum alloy material for tube hydro-forming. Inspection of roughness tester is only applicable to probe method with short distance. In case there is not adhesion burr within the sampling section, roughness obtained through measurement is small. Otherwise, it will be large. It is unknown adhesion burr and measuring error that interferes in variation (Fig. 8) of roughness, which causes that determination coefficient of fitting formula is small.

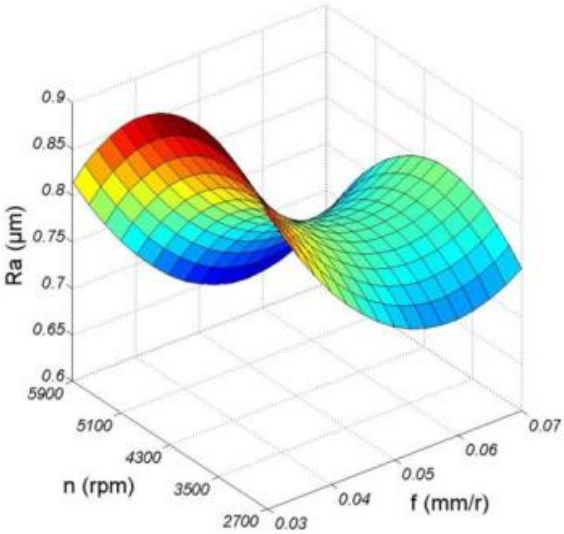


Fig. 7. Roughness of aluminium alloy hole under different process parameters

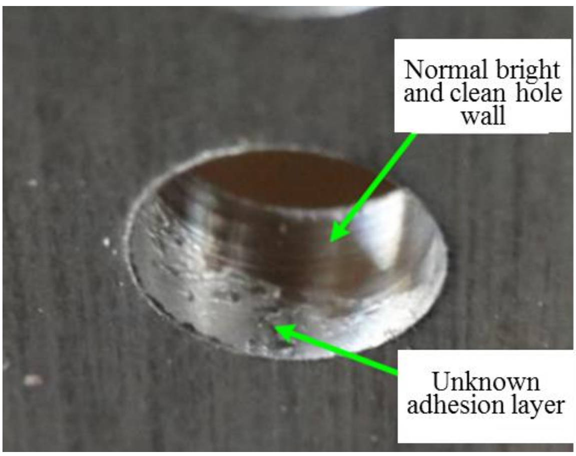
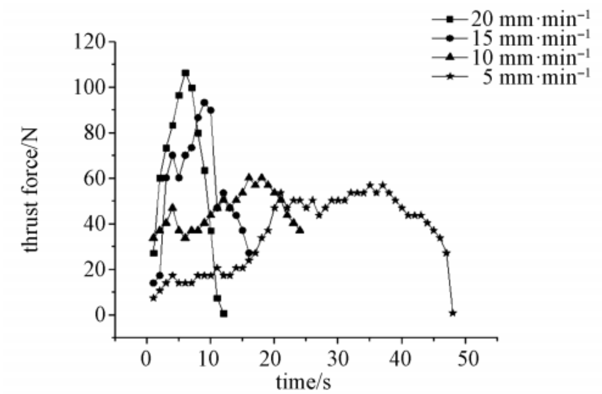


Fig. 8. Aluminium alloy hole after being processed by tricuspid drill

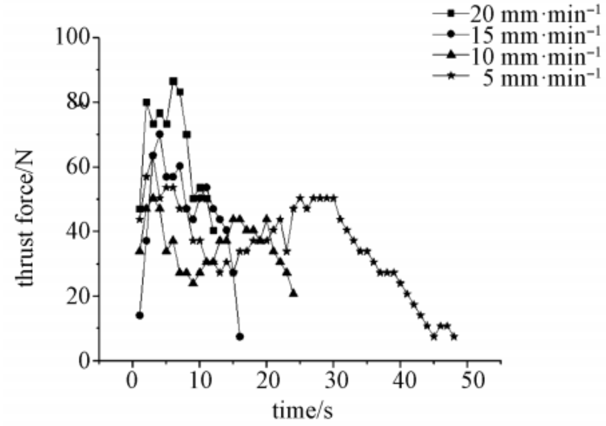
4.4. Relation between axial force and lamination sequence

Hard alloy tool is used to respectively conduct test for two test parts with different lamination sequences so as to obtain data of axial force for drilling of materials in different layers at the time of drilling under different drilling conditions. Variation of axial force generated with different feed rate when it is drilled on the side of aluminium alloy with respective rotating speed of 1000r/min, 2000r/min, 3000r/min, and 4000r/min is shown in Fig. 9.

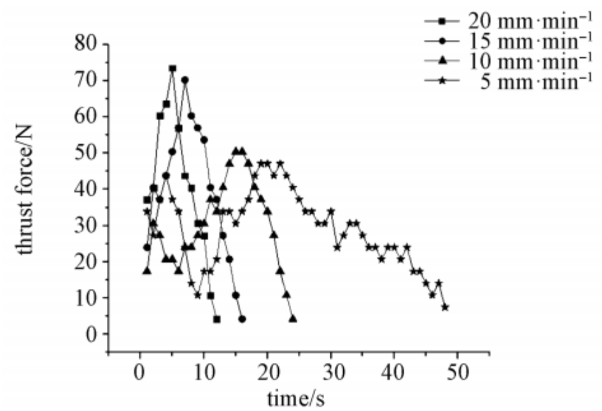
It is shown in Fig. 9 (a) –Fig. 9 (d) that axial force is slightly reduced when



(a)1000r/min



(b) 2000r/min



(c) 3000r/min

Fig. 9. Relation between axial force and feed rate of lamination

rotating speed of tool is increased. Increase of rotating speed for tool makes the frequency of cutting action between it and work-piece be accelerated. However, cutting force is reduced with increase of rotating speed, thus axial force of drilling at that time will be reduced. As feed rate has significant influences on axial force, thus the larger the feed rate is, the larger the axial force is. Meanwhile, it is shown that axial force in the front half part of all curves is higher than that in the later half part, because axial force at the time of drilling aluminium alloy is larger than that at the time of drilling aviation aluminum alloy material for tube hydro-forming.

5. Conclusion

(1) It is found through research on drilling technology of laminated materials that generated axial force at the time of drilling aluminium alloy is larger than that at the time of drilling aviation aluminum alloy material for tube hydro-forming. Main factor which influences axial force is feed rate.

(2) Laminated materials contribute to improving exit quality of aviation aluminum alloy material for tube hydro-forming. Drilling on the side of aviation aluminum alloy material for tube hydro-forming can effectively avoid exit de-lamination and reduce burr. Adding of aluminum alloy in the lamination leads to great change of torque value in the process of drilling, which facilitates tool tipping.

(3) In comparison with other two tools in the test, diamond-like coating tool is more suitable for integrated drilling of CFRP/Al laminated materials with high cutting efficiency and good drilling quality. With increase of drilling quantities, diamond-like coating tool is slowly worn with good drilling quality.

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