# Experiment Study on the Influence of Tool Materials on the Drilling of Thick Stacked Plate of 2219 Aluminum Alloy

G. H. Li, M. Liu, H. J. Qi, Q. Zhu, W. Z. He

***Abstract*—**The drilling and riveting processes are widely used in the assembly of carrier rocket, which makes the efficiency and quality of drilling become the important factor affecting the assembly process. According to the problem existing in the drilling of thick stacked plate (thickness larger than 10mm) of carrier rocket, such as drill break, large noise and burr etc., experimental study of the influence of tool material on the drilling was carried out. The cutting force was measured by a piezoelectric dynamometer, the aperture was measured with an outline projector, and the burr is observed and measured by a digital stereo microscope. Through the measurement, the effects of tool material on the drilling were analyzed from the aspects of drilling force, diameter, and burr. The results show that, compared with carbide drill and coated carbide one, the drilling force of high speed steel is larger. But, the application of high speed steel also has some advantages, e.g. a higher number of hole can be obtained, the height of burr is small, the exit is smooth and the slim burr is less, and the tool experiences wear but not fracture. Therefore, the high speed steel tool is suitable for the drilling of thick stacked plate of 2219 Aluminum alloy.

***Keywords*—**2219 aluminum alloy, thick stacked plate, drilling, tool material.

## I. Introduction

In the process of assembly, the structure of aerospace stacked material is usually connected by riveting and other mechanical methods. The processing quality of connecting holes is the basis and key to ensure the quality of riveted joints. Drilling has been widely used because of its excellent effect on holes making and superior processing efficiency. If the drilling process is not reasonable, it is easy to cause defects such as burr and poor aperture, which affect the quality of riveting and the assembly quality of structural. Therefore, a good drilling process is a prerequisite for ensuring the quality of the assembly.

A series of research works have been carried out on the drilling of stacked plates. Kim et al. [1] divided burr into three categories by analyzing the shape of burr, and analyzed the influence of feed rate and cutting speed on it. Hellstern [2] used a simple pre-compression device in the test of stack drilling, and found that the larger compaction force had better effect on the burr suppression. On the basis of experiment, Melkote et al. [3] summed up the main factors that affect the formation of interlayer burr, such as the sharp angle of the bit, the method of pre-compression, and the position of applying pre-compression force. Bi and Liang [4] proposed a multi-objective optimization algorithm for process parameter optimization during drilling Ti6Al4V and 7075-T6 stacked plates, and found that the spindle speed of 2000 r/min, the feed rate of 0.075 mm/r, the pressure of 0.3 MPa and Ti-Al stacking sequence can achieve the smallest interlayer burr height.

Rajmohan et al. [5], using the axial force, surface roughness, tool wear and burr height as the indexes, through the experimental on Al356/SiC Mica Composites, improved the spindle speed, feed rate, drill type and drilling parameters. Zhang and Zheng. [6] carried out drilling tests on stacked materials composed of Ti-6Al-4V and 7075-T7451 aluminum alloy. The results show that the correct stacking sequence and large compressive force can improve the micro morphology of burrs. Xu et al. [7] carried out drilling tests of aluminum alloy in different drilling parameters and pressing force, and pointed out that the inhibiting effect of axial preload pressure on interlayer burr is greater than that of drilling parameters. Liang [8] investigated the mechanism of an interlayer gap formation and the influence of an interlayer gap in drilling of stacked metal materials and thought that the interlayer gap formation is due to material bending by interlayer thrust force. Li et al. [9] studied the exit burr of aluminum alloy produced by the single side compression. It is pointed out that increasing the prepressing force can significantly suppress the burr height between layers. Zhang et al. [10] analyzed and optimized the drilling parameters for the single component and mixed material stacked sandwich component by robot automatic drilling equipment, special fixture, and spring indicator. Lu [11] carried out the unidirectional precompression drilling test of thin-walled stacked aluminum alloy. The significance of the drilling parameters on the cylindricity of the hole and the interlayer burr was studied by the variance analysis. Gao et al. [12] presented both experimental work and theoretical analysis to understand the interlayer gap formations and non-coaxiality occurrences in the drilling of stacked structures of broad skins and narrow stringers. Bu et al. [13] presented an analytical model of the interlayer gap formation to predict the interlayer burr height, and drilling experiments were developed to understand the difference between the interlayer burr height

G. H. Li is with National-Local Joint Engineering Laboratory of Intelligent Manufacturing Oriented Automobile Die & Mould, Tianjin University of Technology and Education, Tianjin, CO 300222 China (corresponding author, phone: 022-8818-5519; fax: 022-8818-1083; e-mail: lgh790723@163.com).

M. Liu and Q. Zhu are with Mechanical Engineering Department, Tianjin University of Technology and Education, Tianjin, CO 300222 China (e-mail: 1246627012@qq.com, 731073769@qq.com).

H. J. Qi, is with Tianjin Key Laboratory of High Speed Cutting and Precision Machining Technology, Tianjin University of Technology and Education, Tianjin, CO 300222 China (e-mail: qihoujun@tute.edu.cn).

and the interlayer gap. Wang and Hu [14] studied the compacting form of stacked material during automatic drilling of hole. It is considered that the two-side compacting can restrain the additional lamination gap caused by flow stress and thus restrain the burr stroke. Tian et al. [15] studied the formation of drilling exit burr and the influence of interlayer gap on interlayer burr formation and investigated the mechanism of interlayer gap formation in drilling stacked aluminum alloy plates. Su et al. [16] carried out the research of the automatic drilling process aimed at a typical rocket aluminum alloy stacked panel. The influence of tool parameters, machine parameters, pressing force and other factors on the quality of drilling was analyzed to obtain the process parameters for engineering application. Lei et al. [17] aimed to develop a deeply understanding of the relationship between the clamping force and interlayer burr formation. The minimum clamping force, which would just make the stacked sheets entirely contact each other, is considered as the optimal clamping force. Hence, the additional deformation would appear at the contact region when the clamping force keeps rising up. Numerical simulations and experimental verifications are conducted.

From the existing literature, it can be seen that the present studies are aimed at the case of thin stacked plates, but the thick stacked slabs (the total thickness is greater than 10 mm) under the condition of high speed do not involved. Therefore, this paper aimed at the problems which exists in the high-speed hole making for thick stacked plates, including bit break, burr and noise, etc. to do the experimental study. The experiment was done in a high speed milling machining center. Three kinds of tool materials were adopted, and the burr, cutting force, and the drilling quality were investigated. The milling force measuring instrument, projectors, and digital stereo microscope were used for the data collection and chip observation. A proper tool material was determined. It provides basis for drilling making process of aerospace parts.

## II. Experiment of High Speed Drilling

The work-piece is two rectangular sheet samples of 2219 aluminum with the Length and width of 170 mm×100 mm, the thickness is 8 mm and 10 mm, respectively. The experiment is carried out at the XH715D vertical machining center of Hanland, and the experimental setup is shown in Fig. 1. The spindle speed is 6000 r/min, and the feed speed is 850 mm/min.

The tool material which is suitable for the process of aluminum alloy is high speed steel, carbide, and diamond. The used proportion of these three tool materials is shown in Fig. 2. Considering the high price of diamond, three kinds of cutting tools, including cobalt high-speed steel, YG carbide and coated carbide, are chosen for the comparative study.

The standard twist drill with diameter of 6mm was used in the experiment. The cutting force was measured by KISTLER-9257b dynamometer. The machined holes were observed with KEVENCE VHX-1000C digital stereo microscope (Fig. 3), and the aperture was measured by Mitutoyo profile projector (Fig. 4).

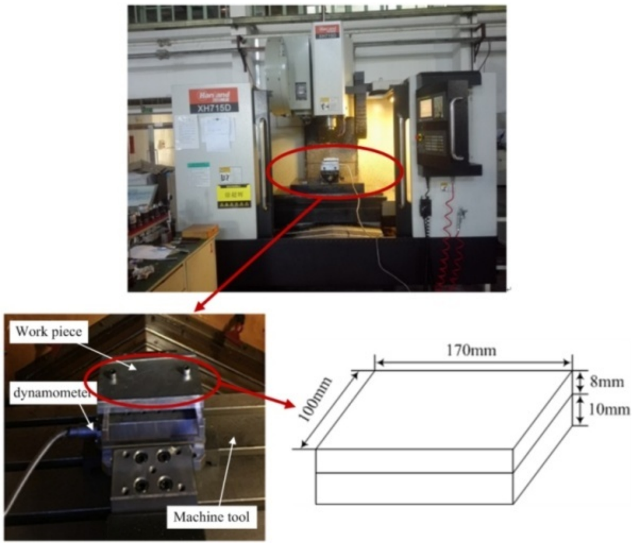



Fig. 1 Experiment device and work-piece

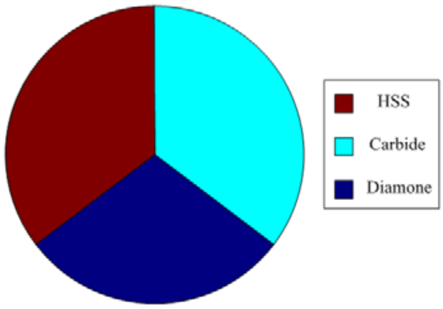



Fig. 2 Common used tool materials for drilling of aluminum alloy

Fig. 3 VHX-1000C digital stereo Microscope

Fig. 4 Mitutoyo profile projector

## III. Experiment Results and Discussion

### A. Number of Machined Hole

Fig. 5 shows the comparison of the number of machined holes before the bit is broken when different tool material is used. Under the given drilling parameters, 26 holes can be made with high speed steel bit, only two holes can be made with carbide bit, and four holes can be made with coated carbide one. Through the shape of chip and crumbs, it can be seen that although aluminum alloy is an easy-to-cut material, but thick stacked plates are difficult to process due to the high temperature caused by the poor cooling conditions. It will increase the plasticity and toughness of work-piece. The long ribbon chip was formed and difficult to scraps discharge. At the same time, the built-up edge at the tool rake face will be further to increase the difficulty of chip removal. The spiral groove is blocked, resulting in the fracture of bit. A large number of holes can be made with high speed steel cutter, and the reason is that, although the hardness of high speed steel cutter is lower than the carbide, the plasticity and toughness are better, therefore, it is not easy to be broken. Although generally the higher cutting performance can be obtained by coatings, but in the process of drilling for thick stacked plates, it is unable to overcome the crumbs problem, leading to the drilling performance which is similar with carbide, and it cannot reflect its advantage.

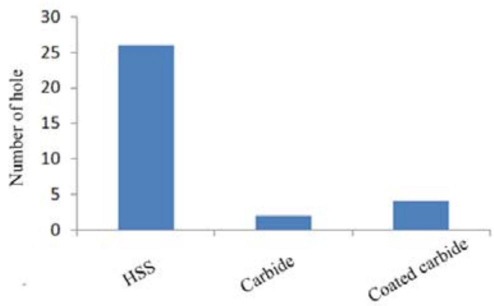



Fig. 5 Number of hole drilling by different tool material

### B. Aperture Size

For the analysis of machining accuracy of processed hole, a Mitutoyo projector is used to measure the hole diameter under the condition of three kinds of tool materials. The measurement results are shown in Fig. 6. The holes with No. 1-26 are made by high speed steel cutter, No. 27 and No. 28 holes are made by carbide cutter, No. 29-32 holes are made by coated carbide tool. It shows that the dimensional accuracy of hole made by HSS Tool is better, and most of the holes can meet the accuracy requirements of H9 (T=30um). The hole made by carbide tool and coated carbide tool has poor dimensional accuracy. This should be due to the instability of the cutting process caused by the crumbs.

### C. Analysis of Burr

For the drilling of the parts of the carrier rocket, the burr mainly consists of interlayer burr and exit burr. In the experiments, the joint between upper and lower plate is better because the samples are machined. The deformation caused by drilling force can be neglected due to the larger thickness of plate and smaller size, and there is no interlayer burr. Therefore, only the exit burrs are observed, and the results are shown in Table I. It can be seen that the height of burr produced by high speed steel tool is smaller, most of which are less than 1 mm. The height of burr produced by carbide tools is larger, reaching to 2.06 mm and 2.23 mm. This is mainly due to instability process when the carbide cutting tool is used. It will result in the fracture of round cap (Fig. 7). The height of burr produced by the coated carbide tool is also smaller, and the single reaches 2.16 mm, and the others are less than 1 mm.

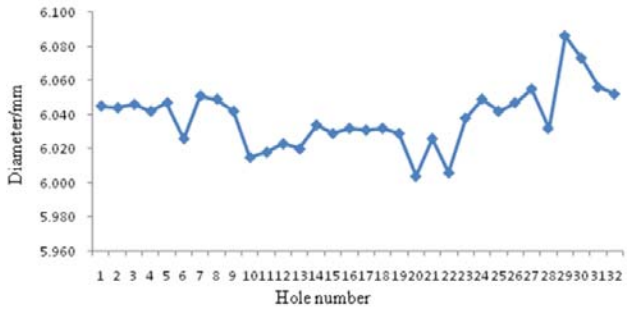


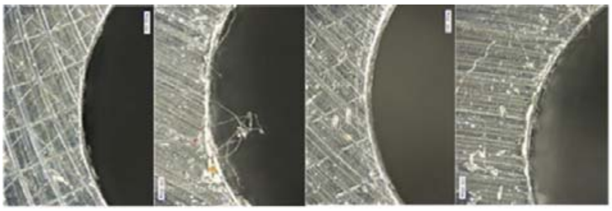

Fig. 6 Change of hole diameter

TABLE I
Burr Height of Hole

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Hole number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Burr height（mm） | ≤1 | ≤1 | ≤1 | ≤1 | ≤1 | ≤1 | ≤1 | ≤1 |
| Hole number | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Burr height（mm） | ≤1 | ≤1 | ≤1 | ≤1 | ≤1 | ≤1 | 1.94 | ≤1 |
| Hole number | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| Burr height（mm） | ≤1 | 2.26 | 2.29 | ≤1 | 2.12 | ≤1 | 2.01 | 0.82 |
| Hole number | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 |
| Burr height（mm） | ≤1 | ≤1 | 2.06 | 2.23 | ≤1 | 2.16 | ≤1 | ≤1 |

Fig. 7 Round map at the exit of hole

The digital stereo microscope was used to obverse the micro burr. Considering the large number of hole, only some representative holes were selected and analyzed. The magnification is 100, and the results are shown in Figs. 8-10. We can see that the micromorphology of holes by high-speed steel tool is better. Both the entrance and exit are relatively smooth, individual holes appear slender micro burr. The entrance of holes by carbide tool is smooth. But, the exit has the large burr due to the rupture of the round cap. The entrance and exit of holes by coated carbide tool are smooth, only one of them has the emergence of chip bonding.



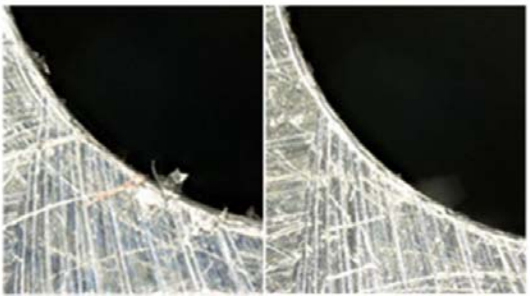
(a) Entrance

(b) Exit

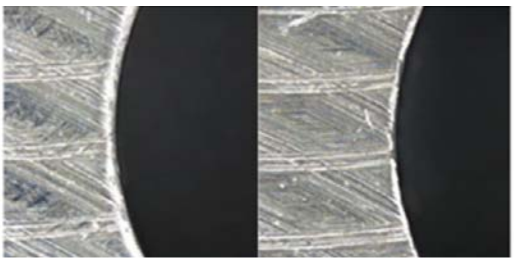
Fig. 8 Burr produced by HSS tool

(a) Entrance (b) Exit

Fig. 9 Burr produced by carbide tool



(a) Entrance



(b) Exit

Fig. 10 Burr produced by coated carbide tool

*D. Analysis of Wear and Breakage of Tool*

In this experiment, the high speed steel bit mainly shows tool wear in the drilling of thick stacked plate, while carbide and coated carbide bit all cause fracture. The macroscopic morphology of tool wear and tear is shown in Fig. 11.

(a) HSS (b) Carbide (c) Coated carbide

Fig. 11 Macroscopic morphology of tool wear and fracture

The wear and fracture of the tool were observed by digital stereo microscope. The results are shown in Figs. 12-14. It can be seen that there is a certain wear in the tool tip of HSS bit, and the wear of cutting edge is smaller, but there is a serious chip sticking. Both the carbide bit and the coated carbide one result in fracture in drilling. The fracture morphology is a typical brittle fracture. Because only several holes have been finished, the wear of bit should be very small. Therefore, the fracture should be caused by torsional damage due to the chip sticking. The lower plasticity and toughness of carbide and coated carbide make them easier to break under torsion.

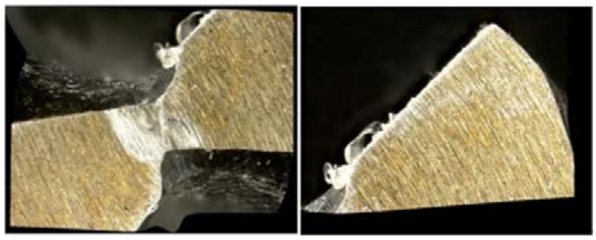


Fig. 12 Wear of HSS bit

Fig. 13 Fracture of carbide bit

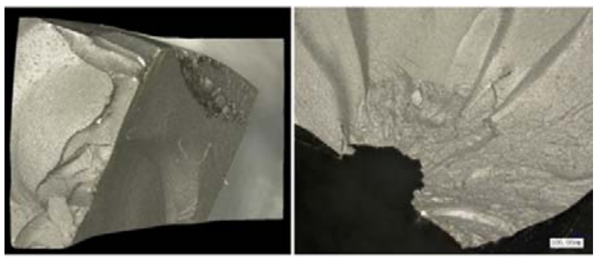
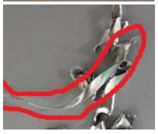


Fig. 14 Fracture of coated carbide bit

*E. Analysis of Chip Shape*

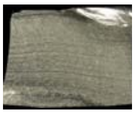
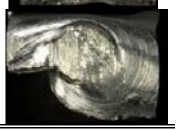
Macroscopic observations of chip produced by three cutting tool materials were done, as shown in Table II. It can be seen that the difference macroscopic morphology of the chip produced by different tool materials is not very significant. There are three different chip forms, i.e. chip, ribbon chip and adhesion chip. Among them, the ribbon chip and adhesion chip are longer, which leads to the difficulty of chip removal and the possibility of chip sticking. This shows that the chip morphology is mainly dependent on the cutting parameters, and not the tool materials.

TABLE II
MACRO MORPHOLOGY OF CHIP

| Tool material | chip | Ribbon chip | Adhesion chip |
|---|---|---|---|
| HSS |  |  |  |
| Carbide |  |  |  |
| Coated carbide |  |  |  |

The microscopic morphology of the chips obtained by three different cutting tools was observed by digital stereo microscope, and the results are shown in Table III. It can be seen that the micromorphology of the chip produced by three different cutting tools is also similar. It is easier to break and for removal. This should be one of the reasons why more holes can be finished when the high speed steel tool is used.

TABLE III
MICRO MORPHOLOGY OF CHIP

| Tool material | chip | Ribbon chip | Adhesion chip |
|---|---|---|---|
| HSS |  |  |  |
| Carbide |  |  |  |
| Coated carbide |  |  |  |

### *F. Analysis of Cutting Force*

The change of the average cutting force during the drilling of high speed steel bit is shown in Fig. 15. It can be seen that the average cutting force is about 790 N. With the increase of the number of machining holes, the average cutting force shows a trend of increasing gradually. This is because the tool shows a certain amount of wear and this gradually increases, which is consistent with the previous results of tool wear. From the exit shape of hole 6 and hole 21, it can be seen that the drilling force decreases when the exit of the hole is smooth, and the drilling force increases when there is the exit burr.

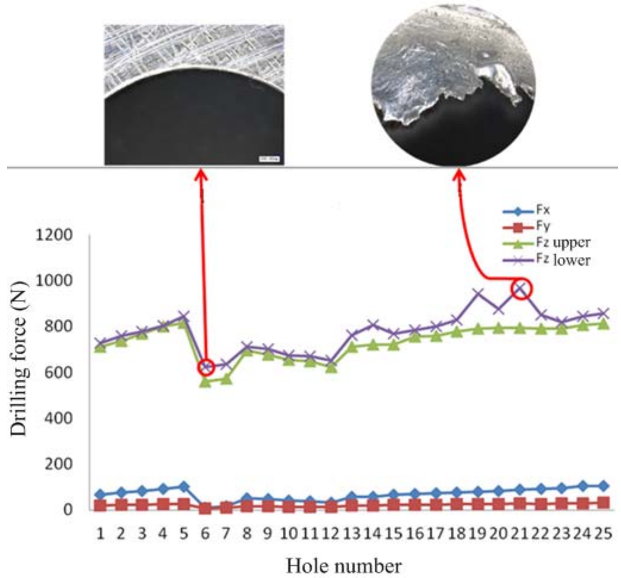



Fig. 15 Change of drilling force when the HSS tool was used

The change of the drilling force of carbide bit with the number of holes is shown in Fig. 16. Its average value is about 710 N, which is less than the drilling force of high speed steel bit. When the third hole is drilling, a sudden increase in cutting force results in a fracture of the tool. The drilling force of coated carbide bit also varies with the number of holes, as shown in Fig. 17. Its mean value is about 700 N, which is basically consistent with that of carbide bit. Instability occurs when the fifth holes are drilled, resulting in fracture of the tool.

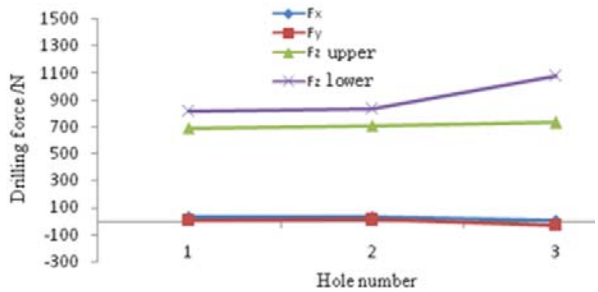



Fig. 16 Change of drilling force when the carbide tool was used

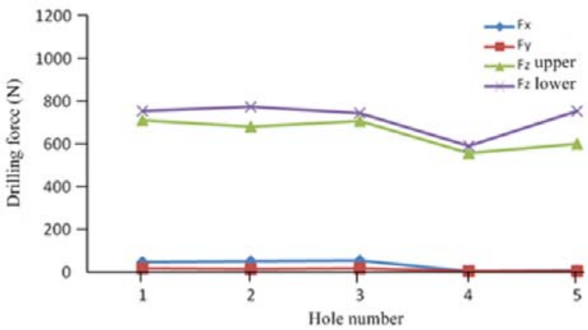



Fig. 17 Change of drilling force when the coated carbide tool was used

At the same time, it also can be found that, for the three kinds of tool materials, the tangential force and radial force are small and negligible when compared with the axial force. So that, only the axial cutting force needs to be analyzed in the future research.

## IV. Conclusion

In this paper, the effect of different tool materials on the drilling of thick stacked plate of 2219 aluminum for launch vehicle was investigated. The main conclusions are as follows,

1) The carbide bit is less ductile than the high speed steel one. It is easy to break because of poor chip discharge and bonding. The high speed steel bit has good toughness and will not break under the condition of small amount of crumbs. It is more suitable for the drilling of thick stacked plate of 2219 aluminum alloy.
2) The macro/micro observations show that the dimension accuracy and surface quality of hole made by high speed steel cutting tools are better. But, those holes, made by carbide tools and coated carbide one, are poor.
3) For the drilling of thick stacked plate of 2219 aluminum alloy, the high speed steel bit mainly shows tool wear in the drilling of thick stacked plate, while carbide and coated carbide bit all show fracture.
4) Three kinds of chip shapes, such as chip, ribbon chip, and adhesion chip, are produced for three kinds of tool materials, and their macro and micro morphologies are relatively close. This shows that the chip morphology is mainly dependent on the cutting parameters, and not the tool materials.
5) Cutting force of high speed steel bit (790 N) > carbide bit (710 N) > coated carbide bit (700 N or so). It mainly depends on the exit burr morphology and chip sticking. The tangential force and radial force can be neglected compared with axial force.

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**G. H. Li,** date of birth is July 1979, graduated from Dalian University of Technology and awarded PhD in December 2010. The major field of study is the mechanism of high speed machining.

He is anassociate professor of the Mechanical Engineering Department, Tianjin University of Technology and Education. And he is the deputy Dean of the National-Local Joint Engineering Laboratory of Intelligent Manufacturing Oriented Automobile Die &Mould. The main paper published as follows.