Optimization design for countersink depth error prediction and compensation of CFRP/Al stacks

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Abstract. The countersink depth accuracy is one of the most important quality indexes of the rivet holes in modern aerospace industry, especially in the drilling of thin-walled carbon fiber reinforced plastic (CFRP) and aluminum (Al) stack. However, the carbon fiber of CFRP is a kind of typical difficult-to-machine material, which results in the terrible wear of the cutting tool, and then the continuously increase of thrust force in the practical machining process, leading to the significant stack deformation and making it difficult to achieve the required countersink depth tolerance. Focusing on the countersink depth control in the drilling of the thin-walled CFRP/Al stack, this paper attempts to optimize the integrated methodology [10] in order to predict and compensate for the stack deformations more accurately. In this paper, an analytical flexible countersinking thrust force model that considers both tool wear and stack deformation is first developed with detailed theoretical analysis. Then a finite element model is established to identify the key features of the stack deformation in the countersinking process. An optimized iterative algorithm, which consists of three nested iterative loops, is designed to calculate the feasible stack deformation and make decision for the error compensation. Finally the optimized methodology are verified by groups of cutting experiments, and the results have shown that the methodology could effectively guarantee the countersink depth accuracy. The work in this paper enables us to understand the generating mechanisms of the countersink depth error in the drilling of the thin-walled CFRP/Al stack, and provides a novel approach to improve the countersink depth accuracy.

1. Introduction

Carbon fiber reinforced plastic (CFRP) and aluminum (Al) stack has been widely used in the modern aerospace industry because of the excellent attributes such as low specific weights and high structural efficiency [1-2]. In order to satisfy the assembly purposes of this special structure, millions of rivet holes need to be drilled out and most of the holes are made by the drilling-countersinking operation [1, 3-4]. The countersink depth accuracy is one of the crucial quality indexes to guarantee the subsequent assembly quality of the aircraft [5]. However, due to the different mechanical properties of the two materials and the low stiffness of this structure, the varying cutting and clamping forces excite the stack leading to significant deformation, which results in less countersink depth accuracy, thus, knowledge and ability are required to predict and compensate for such depth error, and it provides the wider space and stage for new explanations.

Different from the general machine tools, there is a pressure foot in the machining end effector and it could perform clamping operation against the stacks during the whole drilling-countersinking process, and it contributes to reduce cutting vibration of the thin-walled stack and minimize the inter-layer gap and burrs [6]. This machine tool structure has been widely recognized and applied by the
aerospace industry. For such machine operations, there are two categories of methods to control the countersinking depth. The first is the real-time compensation strategy, which means that the stack deformation could be measured through the force or displacement sensors on the pressure foot and compensated in real time based on the feed motion control system [7-9]. The second is the non-real-time compensation strategy, and this method assumes that the stack deformation could be measured and compensated after the spindle feed movement, and this method could reduce machining vibration and guarantee the stability of the compensation process [4, 6].

In spite of these totally deformation measurement and compensation method, the properties of the varying thrust force, especially for countersinking the extreme abrasiveness CFRP, and the deformation mechanism of the stack are still scarcely reported, thus, it limit the further improvement of the countersink depth accuracy. Moreover, the widespread application of CAE/CAM and advanced computational methods provide a new attempt to predict and compensate for the countersink depth. In our previous research [10], the study of countersink depth control in the drilling of thin-walled square Al plate was carried out with theoretical and experimental analysis; the cutting force and deformation mechanism was presented firstly, and then an approach of integrated iterative algorithm was established to predict the plate deformation and make decision for compensating the countersink depth error. However, when it comes to the special CFRP/Al stack with low stiffness, the proposed iterative algorithm in previous research [10] need to be optimized and modified, because the increasing of tool wear and thrust force cannot be neglected in the countersinking process due to the poor machinability and abrasiveness of CFRP, which results in more complex stack deformation than the previous only drilling the single Al plate. What’s more, the prediction and compensation of the countersink depth error in the drilling of CFRP/Al stack is much more difficult, because the coupling effect of cutting force and tool wear and stack deformation has not been well understood.

Given all these considerations, this paper attempts to develop a new approach to optimize the prediction and compensation of the stack deformation for higher countersink depth accuracy. In this paper, an optimized theoretical flexible countersinking thrust force model, that considers both tool wear and stack deformation, is first developed to help to analyze the complex coupling effect. Then a finite element model is established to investigate the CFRP/Al stack deformation with the key input of thrust force based on the practical machining process, and an optimized iterative decoupling algorithm is established to predict the countersink depth error and calculate the compensation value. Finally the proposed model and the optimized approach are verified by the multivariate thin-walled CFRP/Al countersinking experiments.

2. Analysis of flexible thrust force

The whole CFRP/Al stack drilling-countersinking process can be simplified into two machine operations, the first is the clamping operation and the second is the drilling and countersinking operation. More details about the cutting process and the cutting tool can be found in [10, 11]. In our previous work [11], the effect of cutting tool wear on the CFRP/Al stack countersinking thrust force has been analyzed with developing a theoretical model, and there are three distinct abrasion region in the flank wear land of the cutting edge, and the cutting force that happens under the flank wear land is a continuously increscent component and it contributes a lot to the variation of the total countersinking thrust force.

Therefore, in order to predict and compensate for the countersink depth error, it is significant to analyze the special coupling relation between the stack deformation and tool wear and thrust force. As shown in figure 1, \( H \) and \( H_{GA}, H_{AB}, H_{BC} \) respectively represent the length of projection of the whole flank wear land and the abrasion regions of 1, 2, 3 in the axial direction of the cutting tool, and this paper assumed that the nominal countersink depth is equal to \( H \), which is also equal to the countersinking feed depth of the cutting tool based on the practical machining process. According to the above-mentioned definition and assumption, the relationship between the real countersink depth \( C_d \) and the stack deformation \( D_{ef} \) can be expressed as

\[
H = C_d + D_{ef}
\]
Based on our previous research [11], an approach of infinitesimal elements is used to model the influence of tool wear on the countersinking thrust force: the countersinking edge can be divided into finite elements, the differential cutting forces on the engaged infinitesimal elements can be modeled firstly and then integrated into the resultant thrust force. The expression of the CFRP/Al stack countersinking thrust force \( R_c \) can be represented as [11]

\[
R_c = 2\int_0^3 dF_y V_c + 2\int_0^3 dF_z W_c
\]

where \( dF_y \) and \( dF_z \) represent the differential cutting forces, \( V_c \) and \( W_c \) are the cutting parameter coefficients and their detailed definitions and the theoretical expressions can be found in [11]. And then a more concise equation has been formulated, that is \( R_c = R_{\text{wear}} + R_{\text{fresh}} \), which means that total thrust force can be expressed in the sum form of force increment caused by tool wear \( R_{\text{wear}} \) and the initial thrust force \( R_{\text{fresh}} \) [11].

According to equation (1), the stack deformation could affects the real countersink depth and changes the upper limit of integral \( l_{\text{max}} \) in equation (2), which can be expressed as \( l_{\text{max}} = C_d / \cos \rho_c \), and \( \rho_c \) is the is the half point angle of the countersink. Therefore, it is assured that the classification modeling need to be carried out based on the stack deformation value and the length of the three abrasion regions.

Case one: \( 0 \leq D_{ef} < H_{BC} \). As shown in figure 1, in this case, the abrasion regions of 1 and 2 of the cutting tool are in the state of complete contact with the workpiece during the countersinking process, while the abrasion region 3 is in the state of partial contact. Therefore, the following inequality about \( l_{\text{max}} \) makes sense.

\[
\frac{H_{GA} + H_{AB}}{\cos \rho_c} < l_{\text{max}} \leq \frac{H_{GA} + H_{AB} + H_{BC}}{\cos \rho_c}
\]

(3)

Case two: \( H_{BC} \leq D_{ef} < H_{BC} + H_{AB} \). In the same analysis method, the inequality about \( l_{\text{max}} \) can be expressed as

\[
\frac{H_{GA}}{\cos \rho_c} < l_{\text{max}} \leq \frac{H_{GA} + H_{AB}}{\cos \rho_c}
\]

(4)

Case three: \( H_{BC} + H_{AB} \leq D_{ef} < H_{BC} + H_{AB} + H_{GA} \). The inequality is represented as

\[
0 < l_{\text{max}} \leq \frac{H_{GA}}{\cos \rho_c}
\]

(5)

Based on the differential forces analysis on the engaged infinitesimal cutters of the countersinking edge and the modeling approach of integral operation [11], the comprehensive influence of tool wear and stack deformation on the thrust force can be formulated particularly with the classified integral
limits of inequalities (3) to (5). Because there are three cases of the upper integral limit in the theoretical model, the final countersinking thrust force is also classified into three cases.

Case one: \( 0 \leq D_{ef} < H_{BC} \). Based on inequality (3), the whole integral limit need to be divided into three parts because the integration computing is required separately for abrasion regions of 1, 2 and 3. That is from 0 to \( H_{GA}/\cos \rho_c \) first, and from \( H_{GA}/\cos \rho_c \) to \( (H_{GA}+H_{AB})/\cos \rho_c \) next, and then from \( (H_{GA}+H_{AB})/\cos \rho_c \) to \( L_{max} \). The wear-dependent increment of the countersinking thrust force \( R_{\text{wear}} \) can be expressed as

\[
R_{\text{wear}} = R_{\text{wear1}} + R_{\text{wear2}} + R_{\text{wear3}}
\]

where \( R_{\text{wear1}} \), \( R_{\text{wear2}} \), and \( R_{\text{wear3}} \) respectively represent the increment of the thrust force in the abrasion regions based on the integral limit partition, and the definition and evaluation of other parameters in the equations can be found in [11].

Case two: \( H_{BC} \leq D_{ef} < H_{BC} + H_{AB} \). Similarly, based on inequality (4), the whole integral limit need to be divided into two parts, that is first from 0 to \( H_{GA}/\cos \rho_c \) and then from \( H_{GA}/\cos \rho_c \) to \( L_{max} \). The force \( R_{\text{wear}} \) can be expressed as

\[
R_{\text{wear}} = R_{\text{wear1}} + R_{\text{wear2}}
\]

Case three: \( H_{BC} + H_{AB} \leq D_{ef} < H_{BC} + H_{AB} + H_{GA} \). Based on inequality (5), the whole integral limit is from 0 to \( L_{max} \), and the force \( R_{\text{wear}} \) can be expressed as

\[
R_{\text{wear}} = \frac{2E_r(V_c + \mu W_c)}{\cot \rho_c} \left( \frac{k_{\Delta f}(n)H_{GA}}{\cos \rho_c} + \left( e_{\Delta f}(n) - \frac{k_{\Delta f}(n)(T + D_{ef} - H)}{\cos \rho_c} \right) \ln \left( \frac{T + D_{ef} + H_{GA} - H}{T + D_{ef} - H} \right) \right)
\]

As for \( R_{\text{cfresh}} \), it is equal to the countersinking thrust force if using the fresh edges [11], which can be calculated based on the model developed in [1, 12], and the relationship between this force and stack deformation has been analyzed in [4]. Thus, the initial thrust force are no more discussed detailed in this section.

3. Modelling of stack deformation

Because the stack deformation is the significant factor that results in the countersink depth error, it is necessary to develop the deformation prediction model for the error compensation. However, it may be difficult to accurately calculate the stack deformation analytically, especially for the varying clamping and cutting forces acting on the stack structure of CFRP/Al. In this case, the finite element analysis (FEA) method is one of the effective choice. The input to the FEA model is the stack material properties and the boundary conditions based on the practical experimental apparatus, and the thrust force predicted by the analytical model in section 2. The experimental apparatus are shown in figure 2, and the CFRP/Al stack, with the length and width of 125 mm \( \times \) 125 mm and the thickness respectively of 3.4 mm/4 mm, are mounted on the fixture in the form of cantilever in order to approximate the practical machining conditions. The CFRP plies are made of carbon/epoxy prepregs, and the material properties of the stack can be found in the previous work of our group [3].

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A 3-D FEA model is built to analyze the stack deformation in the countersinking process, as shown in figure 3, and this simulation model is developed with the same dimensions and material properties to the practical stack shown in figure 2. Two groups of holes, respectively labelled with A1 to A5 and B1 to B5, are designed to be drilled in the positions with a different stiffness distribution. Two different clamping forces of 230 N and 346 N are used in this simulation and the next experiment section, and the clamping forces are exerted by the pressure foot driven by the pneumatic cylinder with the calibrated pressures of 0.1 MPa and 0.15 MPa respectively.

![Figure 2. The experimental apparatus](image)

![Figure 3. The FEA simulation model](image)

What’s more, the thrust force is an input to this simulation model, which results in the stack deformation and then the smaller countersink depth. However, predicted deformation also has much effect on the thrust force, as mentioned in section 2, and the thrust force tends to become smaller due to the stack deformation, until the equilibrium state is achieved. Therefore, the obtained deformation only based on the static FEA is actually not the final feasible stack deformation, and the coupling effect between these factors need to be decoupled by a more advanced computational method [10], which will be discussed in the next section in detail.

4. Optimization of the iterative algorithm

Based on our previous work [10], an approach of integrated flexible iterative algorithm has been proposed to search for the equilibrium state of force and deformation in order to predict the countersink depth error. However, when it comes to the thin-walled CFRP/Al stack machined with a worn tool, the proposed algorithm in the previous research [10] need to be optimized, especially for the calculation method of compensation value.

According to the above-mentioned analysis of the thrust force and deformation in the drilling of cantilevered CFRP/Al stack, the optimized iterative algorithm is designed and the computational procedure is described in the flowchart, as shown in figure 4: with the initialization of the parameters and the modelling of the thrust force and deformation, the three nested iterative loops constitute the core content of this algorithm. The inner loop, which can be referred as $i – \text{loop}$, is used to calculate the deformation value, and the detailed iteration process of the $i – \text{loop}$ can be found in [10]. Based on the inner loop, the middle loop, which is referred as $j – \text{loop}$, is designed to compute compensation value. The outer loop, which is referred as $t – \text{loop}$, is used to record the drilling position.

In this iterative algorithm, $w_{i,j,t}$ and $F_{i,j,t}$ respectively represents the calculated stack deformation and cutting force in the drilling position $(x_i, y_i)$. $TC_{i,t}$ is the computed feed depth of the cutting tool, and $DEF_{i,j,t}$ is the computed compensation value, $H$ is the nominal countersink depth. There are two functions in the flowchart, the first is the deformation function, $w = w(F)$, and its essential attribute indicates that the stack deformation increases with the increase of cutting force in the machining process; the second is the cutting force function, $F = F(TC - w)$, and the essential attribute is that the cutting force increases with the increase of real cutting depth $(TC - w)$. The core point of the
optimized iterative algorithm is that, after the parameters initialization, the feed depth of the tool is $TC_{0,t} = H$, however, due to the low-stiffness of the stack, the deformation $w_{i,0,t}$ of the equilibrium state can be calculated based on the inner loop and it is the countersink depth error without any compensation. Then, with the assignment of $w_{i,0,t}$ to the first compensation value $DEF_{0,t}$, the feed depth is modified to $TC_{1,t} = H + DEF_{0,t}$, however, another stack deformation of the equilibrium state $DEF_{1,t}$ can be calculated and difference value $(DEF_{1,t} - DEF_{0,t})$ is construed as the deformation increment for the compensated feed depth $DEF_{0,t}$. Based on the middle loop, the feed depth can be continuously revised until the compensation value reach the convergence precision, and the final compensation value $DEF_{f,t}$ is the computed one to achieve the required countersink depth. Finally the countersink depth error and the compensation value in this drilling position has been figured out, and the calculation of the next hole start according to the outer loop of this iterative algorithm.

5. Experiment and discussion
Groups of cutting experiments are carried out in order to verify the optimized methodology proposed in this paper. The experimental apparatus and CFRP/Al stack are shown in figure 2, and a countersink depth gage of Trulok SR903 is used to measure the countersink depths. The nominal countersink depth

![Flowchart for the optimized iterative algorithm.](image-url)
is 2.50 mm. The clamping forces and the drilling positions has been described in section 3. A worn cutting tool, with the diameter of the drill bit of 7.928 mm and point angle of the countersinking edge of 100°, is used in this study, and the micrograph of the wear condition of the countersinking edge of the tool is shown in figure 5. figure 6 shows the theoretical and experimental thrust force before the countersinking experiments, and it is assured that the cutting force model works well.

Based on the optimized methodology proposed in this study, the theoretical calculated deformation and compensation values are shown in figure 7. It can be seen from this figure that the compensation value is bigger than the deformation value in any drilling position, and as for the cantilevered stack, these two values of group B are much bigger than that of group A. What’s more, the increase rate of the countersinking thrust force is about 16 N /10 holes based on the calibration, and the designed experiment order is Group A/230N firstly, then B/230N, thirdly B/346N, and finally A/346N, thus, the calculated thrust force need to be modified in these four groups.

The experiment results of countersinking with and without compensation are shown in figure 8. In order to eliminate the effect of cutting tool setting error and stack installation error, a method of trial cut is used before the experiment. It can be seen from this figure that the countersink depths that drilled without compensation are more sensitive to the changes of clamping force and stack stiffness, for example, if the clamping force is 230 N, the variation range of the countersink depths of Group A that drilled without compensation are from 2.386 mm to 2.432 mm, with the average value of 2.415 mm, while that of the holes drilled with compensation in the same conditions are from 2.502 to 2.52 mm, with the average value of 2.510 mm. Therefore, the optimized iterative algorithm proposed in this paper could guarantee the countersink depth accuracy.
Although the effectiveness of the methodology, including the thrust force model and the optimized iterative algorithm, developed in this paper has been validated by experiments, there still exists some deviations between the required countersink depth and the average values of the countersink depths of the holes drilled with compensation. It is mainly results from two categories of influential factors: the first is the random and system errors of the experimental equipment, such as the feed motion error of the machine tool and the calibration error of the clamping forces; the second and the important is the system errors of this methodology, such as the simplification errors of the thrust force model, and the calculation error of the stack deformation FEA model.

![Figure 8. The experiment results.](image)

**Figure 8. The experiment results.**

### 6. Conclusion

In this paper, an optimized methodology that focus on the problem of accurate control of the countersink depth in the drilling of thin-walled CFRP/Al stack has been developed with detailed theoretical analysis and experimental verification. The proposed approach is based on modeling of the cutting force that considers the effect of both tool wear and stack deformation, identifying the key features of this deformation in the CFRP/Al stack countersinking process; and the modeling of these two factors provides an input for the downstream optimized iterative algorithm to calculate the feasible deformation value and the compensation value. Groups of countersinking experiment have been carried out and the results show that the optimized integrated methodology proposed in this paper could effectively guarantee the countersink depth accuracy. What’s more, this optimized algorithm is also a programmable alternative for designing new countersinking approach that take the tool wear and stack deformation into consideration.

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