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FINITE ELEMENT MODELING OF BURR FORMATION IN DRILLING OF A MULTI-LAYERED MATERIAL

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ABSTRACT

For an optimization of a drilling process to minimize burr formation, control chart or empirical model from design of experiment can be used. However, direct measurement of inter-layer burr is limited experimentally in the case of drilling through a multi-layered material, which is a common process in aerospace industry. A finite element model that can quantitatively predict the inter-layer burr formation from workpiece material properties and process conditions would significantly reduce the cost and time for building an empirical model. In this study, a finite element model using material properties of stainless steel 304L from previous work was applied to simulated burr formation process during drilling of a multi-layered material. Simulation showed inter-layer burr formation along with entrance burr formation. A quantitative prediction scheme of burr size using node displacement tracking for burr thickness and height was presented.

INTRODUCTION

Drilling burr prevention or deburring process in aerospace industry has been one of the major concerns in manufacturing of an commercial aircraft. Selecting tools and process parameters according to the workpiece material and hole quality requirement is critical for the minimization or prevention of burr formation. However, analytical model of the interaction between process conditions, material properties and burr formation, which can predict burr formation from the process conditions and material selections are limited. Besides an analytical model, several empirical models from extensive design of experiment tests have been developed for several materials [1,2]. These empirical models or drilling burr control charts can be used for prediction of the size and type of exit burr during drilling from process conditions, drill geometry and workpiece material. However, the use of these control charts is limited to the drilling through a single layered material. In aerospace industry, to ensure high strength to weight ratio, stacked multi-layered material is commonly used. The inter-layer burr or inter-layer chip breakout during drilling through multi-layered material can cause serious structural safety problems of an aircraft and should be removed carefully.

A finite element model that can simulate inter-layer burr formation process will help engineers to investigate inter-layer burr formation mechanism and further help to build an analytical model for process optimization. Park [3] developed a two dimensional FEM model of

burr formation in orthogonal cutting of Al1100 and SS304L and suggested four step burr formation mechanism. Guo [4] and Min [5] simulated the burr formation in drilling process using 3D FEM model. In Min's FEM model, different types of burr were generated with different process conditions. Based on these studies, Choi [6] simulated inter-layer gap formation process in drilling through double-layered SS304L plates. In this paper, simulation results from the FEM model developed in the previous work [6] are introduced
.

FINITE ELEMENT MODEL

General-purpose FEM software, ABAQUS/CAE™ was used to build and run a model. The boundary conditions and model geometry is shown in Figure 1. Two 1.5mm thick SS304L plates in size of 8mmx8mm were used to simulate elastic bending and inter-layer gap formation during drilling. At four fixture locations, every displacement degree of freedom of the nodes located on the top surface of first layer and bottom surface of second layer were fixed to zero throughout the simulation. The diameter of each fixture was 4mm. The contact behavior between the two plates was assumed as a simple tangential friction with friction coefficient of 0.3.

A 3D meshed conventional drill bit model with 6mm diameter, 130-degree point angle and 40-degree helix angle was generated with specially designed mesh generator software and imported into ABAQUS model. Workpiece plate was meshed with fine elements near the drilling region and with coarse elements in other region to reduce total number of elements in the model. Drill bit elements were assumed to be rigid and no deflection or heat dissipation in drill bit was allowed in the model. Feed and speed of drilling was assigned to this rigid drill bit by assigning velocity boundary conditions. A feed of 0.7 mm/sec and a speed of 1000 rpm were used. The interaction between the drill bit surface and workpiece was modeled as contact mechanism with simple tangential friction behavior with friction coefficient of 0.3.

In metal cutting process, significant amount of heat that can affect the material properties is generated and dissipated to chip and workpiece. Because Lagrangian method simulation with element deletion was used, chip formation during drilling was not modeled and heat dissipation to chip was ignored in this model. This assumption is reasonable because heat cannot be easily dissipated to workpiece material due to high strain rate. Hence adiabatic thermal assumption is made and the work to heat conversion factor of 0.8 is assumed. Temperature-dependant plasticity and elasticity of stainless steel 304l (SS304L) [6] was defined as the material properties.

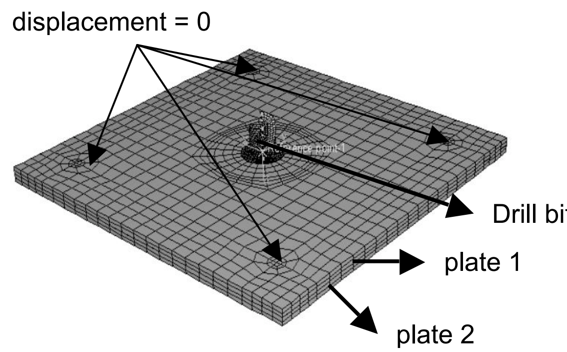


FIGURE 1. FINITE ELEMENT MESH AND BOUNDARY CONDITIONS FOR DRILLING SIMULATION.

Failure criterion based on the strain rate and strain was used. Any element that failed to meet the failure criterion was eliminated from the model in each increment. The plastic strain at failure, $\bar{\varepsilon}_f^{pl}$, was assumed to be 1.52 for the convergence of integration throughout the model and burr formation simulation.

INTER-LAYER GAP VARIATION AND BURR FORMATION

Spatial displacement of a node located on the perimeter of the hole was recorded throughout the simulation. Figure 2 shows the observation node location and the directions of displacement. Figure 3 shows the time variation of the feed direction displacements of the node on the entrance surface of the second plate (node 2) and exit surface of the first plate (node 1).

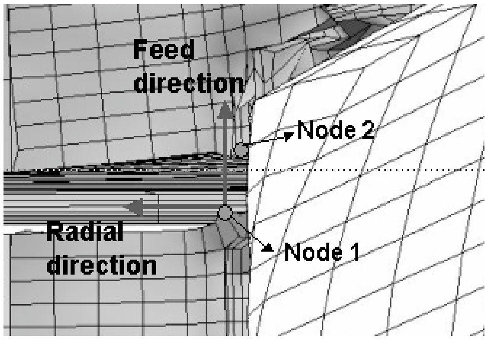


FIGURE 2. OBSERVATION NODE LOCATION AND DIRECTION OF DISPLACEMENT.

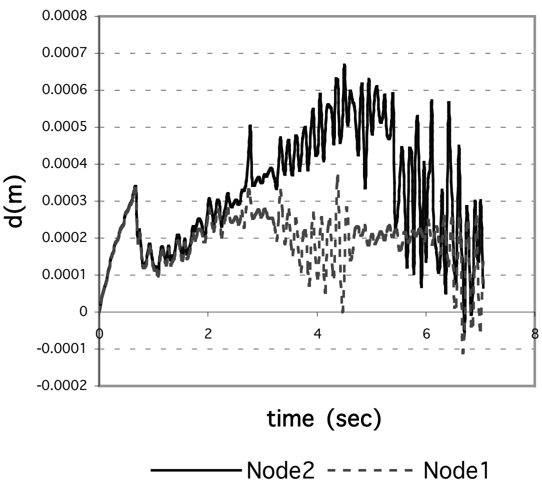


FIGURE 3. FEED DIRECTION DISPLACEMENTS OF NODE 1 AND NODE 2.

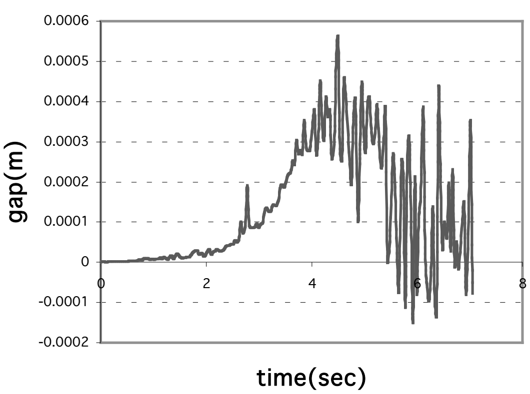
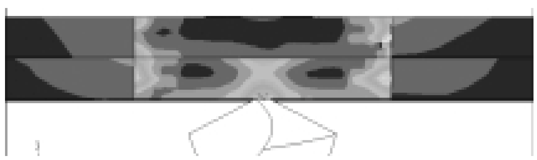


FIGURE 4. INTER-LAYER GAP VARIATION.

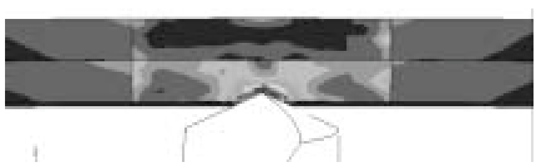
The distance between the two-observation nodes represents the gap formed between the two plates. Time variation of this distance is shown in Figure 4. In the finite element simulation, strain was evaluated element by element and any element that met the failure criterion was deleted from the model. Hence material removal is not a continuous process in the model. Instead, the material removal process in the model consists of three steps. First, failure criterion at some of the elements is met and those elements are eliminated from the model. Second, whole plate spring back to touch the drill bit because there are empty space between plate and drill bit after element deletion. Third, stress concentration occurs at the newly exposed element edge because it is sharp. This process continues and causes the oscillation of the displacement in figure 3 and 4, since there would be vibration effect from this non-continuous process. The amplitude of this oscillation would decrease as the mesh size decreases.

Inter-layer gap and burr formation process is shown in Figure 5, which shows the Mises stress contour and deformed shape. Until around 0.7 second, two plates bend elastically and no gap between the two layers is observed. Axial displacement of the observing nodes increases almost linearly up to 0.34 mm. No material failure occurs in this stage. Plastic deformation is limited near the area around the drill tip engaged to the drilling. At around 0.7 second, the displacement of the observing nodes falls down to 0.13 mm and a small gap starts to form and increases as the drill advances. Material starts to fail around the drill tip area and element elimination starts to occur at this stage. Drill bit starts to engage the second layer at around t = 2.6 second. Inter-layer gap starts to increase significantly as the first layer starts to spring back and the second layer is pushed toward feed direction by the drill bit. Inter-layer gap reaches the maximum at around t = 4.5second and starts to decrease as the second layer starts to spring back as the plastic deformation of outer surface increases. From around t = 5.5 second, the displacement of the node on the entrance surface of the second layer (node 2) starts to go below that of the node on the exit surface of the first layer (node 1). This means that the second layer touches previously formed inter-layer burr. The fluctuation of the node displacement shows the vibration of the plate and element deletion effect together. Simulation shows both layers vibrate during drilling and the vibrating second layer touches previously formed inter-layer burr. This interaction between the second layer and the inter-layer burr will affect the size and shape of the burr and chip break out phenomenon. In this simulation, maximum gap size was much larger than the inter-layer burr height and this interaction was observed only after t = 5.5 second.

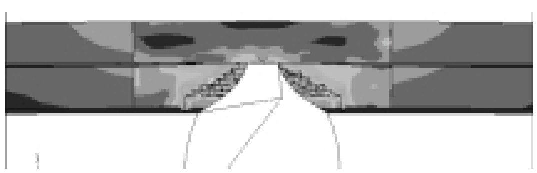
Inter-layer burr formed on the exit surface of the first layer after drill bit completed the penetration of the first layer is shown in Figure 6.



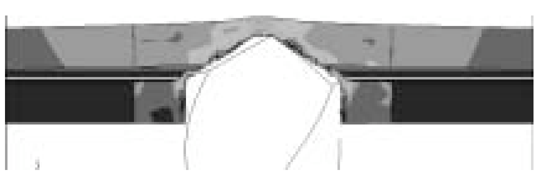
t = 0.65 sec



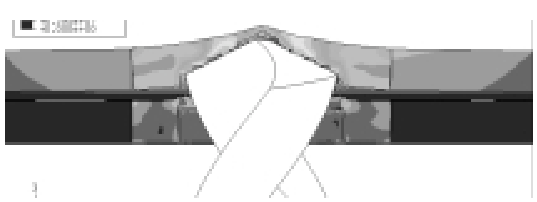
t = 0.875 sec



t = 2.6 sec



t = 4.374 sec



t = 5.375 sec

FIGURE 5. INTER-LAYER GAP AND BURR FORMATION PROCESS.

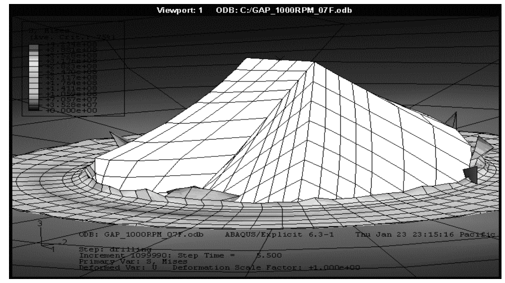


FIGURE 6.INTER-LAYER BURR.

COMPARISON WITH THRUST FORCE VARIATION

Figure 7 shows experimentally obtained drilling thrust force variation during single layer drilling [7] and figure 8 shows feed direction displacement of measurement point on the exit surface of the first layer (node 1) during first 2.8 seconds of FEM drilling simulation of multi-layered material. By assuming a linear relation between the plate deflection at the center and thrust force, it is possible to roughly compare the thrust force variation with the node displacement in feed direction because the hole diameter is relatively small compare to the whole plate size. The variation of feed direction node displacement from FEM showed good correlation with the thrust force variation from experiment.

In the first stage of drilling, relatively large thrust force, as compared to steady state drilling force, was observed. This is because only a small portion of drill bit is engaged in drilling before steady state drilling where all of the cutting edge of drill bit is engaged in cutting. Compared to steady state cutting, relatively large thrust force pushes the workpiece material in this stage.

In FEM simulation, this phenomenon was simulated in a different manner. Before the strain at the drill web region workpiece elements reaches the material failure criterion, workpiece material elastically bends because simple friction behavior was used between drill bit and workpiece. This elastic bending continues until the failure criterion is met at the drill web touching region. In elastic bending stage, almost no gap forms and gap starts to increase at t = 0.67 sec when the material failure and plastic deformation starts to occur.

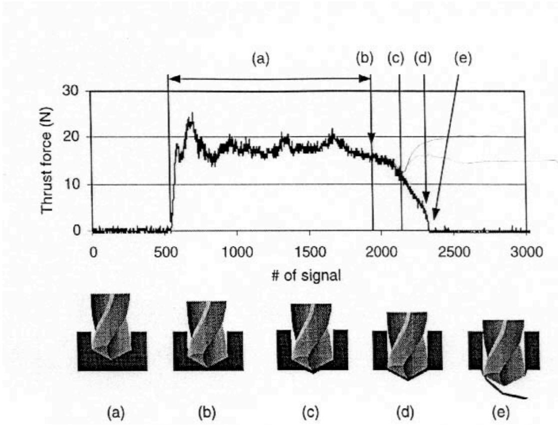


FIGURE 7. DRILLING THRUST FORCE DURING DRILLING OF A SINGLE LAYERED MATERIAL [7]

As soon as failure criterion is met at drill web touching region, workpiece plate moves back to d ≈ 0.12 mm and d increases as the drill moves further, where d is feed direction displacement of observation node. From this point, material in front of the drill tip experiences severe plastic deformation and failure [6].

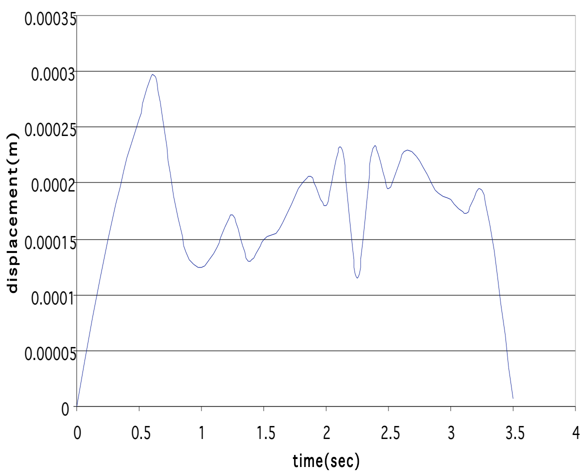


FIGURE 8. FEED DIRECTION DISPLACEMENT OF NODE 1 FROM FEM

ENTRANCE BURR FORMATION

Entrance burr was also observed in the simulation. Figure 9 shows entrance burr formation process during drilling. At the beginning of the process, material bumped up on the perimeter of the drill-engaging region because of the indenting action of the drill bit. As more part of cutting edge engages in machining, hole diameter becomes larger and before all the cutting edge is engaged in the machining, small amount of bumps of material is always observed on the perimeter of the hole (t = 1.5 ~ 1.875 sec in figure 9). When almost all cutting edge is engaged, the shape of bump on the perimeter starts to change from a smooth, round shape to a biased, shaper shape (t = 2.125). Finally, as all drill bit engages, i.e. drill completely penetrates through the first layer; entrance burr remains on the surface. (t = 2.25 ~ 2.625 sec). The shape of remaining burr is uniform around the hole and slightly bent outward of the hole.

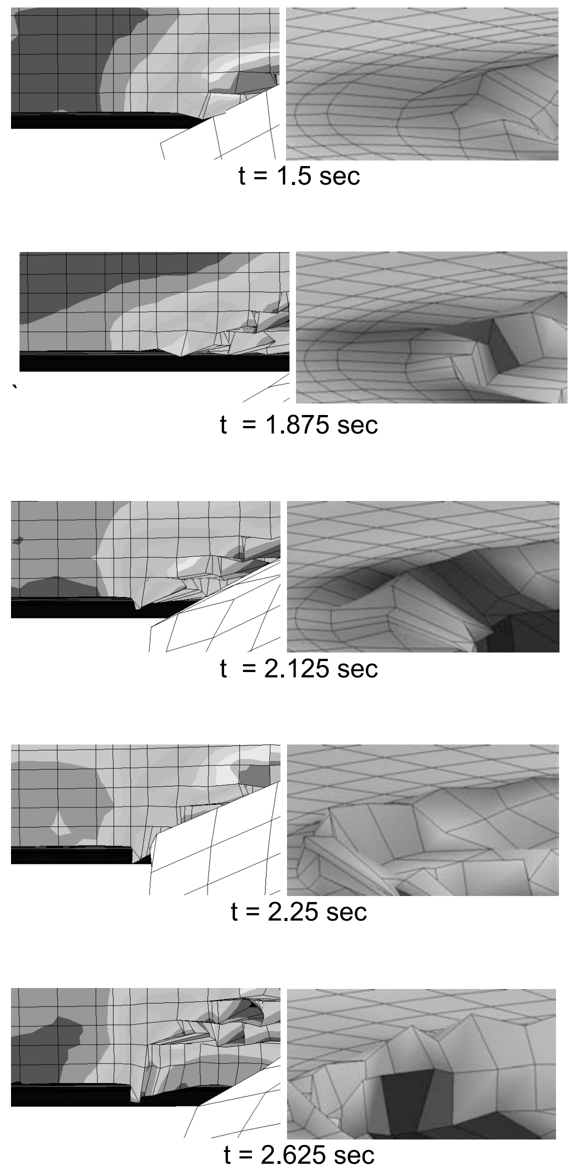


FIGURE 9. ENTRANCE BURR FORMATION (LEFT : CROSS SECTION VIEW, RIGHT: OBLIQUE VIEW, FILPPED OVER).

QUANTITATIVE PREDICTION OF INTER-LAYER BURR SIZE

For a quantitative prediction of burr size, failure criterion based on experimental result and finer mesh size should be used. Figure 10 shows the displacement variation of the observation node on the exit surface of the first layer (node 1) along with feed direction and radial direction. After drill bit completely penetrates through the first layer, measurement point should come back to its original position because there is no plate-scale plastic deformation of the first plate. However, as shown in figure 10, it doesn't come back to its original position. This amount of displacement corresponds to materials local plastic deformation, which corresponds to predicted burr height. Also, radial direction displacement of observation node is shown. After drill bit penetrates through the first layer, radial direction displacement remains due to the plastic deformation of material. This permanent displacement of observation node can be considered as burr thickness. The result showed about 200μm of thickness and 200μm of height of the inter-layer burr. Since many assumptions on material behavior under drilling process, simplified failure criterion and relatively large meshes were used; this quantitative result cannot be directly used as a prediction of burr size. More simulations with various mesh sizes, failure criterions and process parameters should be done and the results should be compared with experimental result for a robust FEM model.

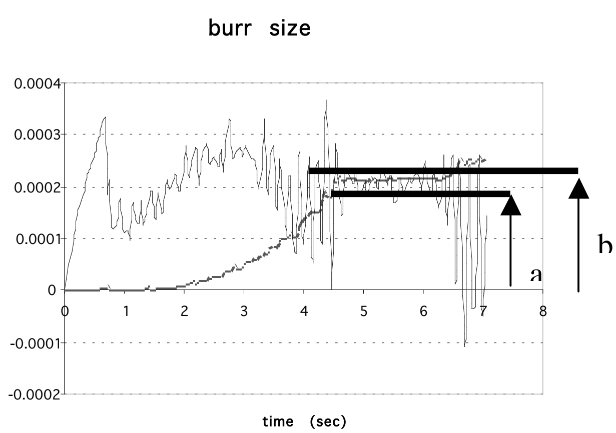


FIGURE 10. BURR SIZE ESTIMATION (a: BURR HEIGHT, b: BURR THICKNESS.

CONCLUSION

The inter-layer and entrance burr formation process during drilling was observed with a FEM simulation. Workpiece bending due to the thrust force from the FEM simulation showed similar variation observed in experiment. From the feed and radial direction displacement variation of the observation node, which was located on the surface at the perimeter of the drilling hole, burr size was estimated quantitatively. For a robust simulation tool, further study is needed on the material failure criterion and the contact behavior modeling between drill bit and workpiece.

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