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# MODELING OF INTER-LAYER GAP FORMATION IN DRILLING OF A MULTI-LAYERED MATERIAL

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## Abstract

With increases in the use of multi-layered material in the aerospace industry to reduce weight while still meeting strength requirements, studying inter-layer burr formation in drilling of a multi-layered material becomes more important. Inter-layer gap formation due to material bending by drilling thrust force has significant effect on inter-layer burr formation. A finite element model for inter-layer gap formation in a multi-layered material was proposed. A gap formation was initiated by initial difference in elastic bending of layers and developed by plastic deformation of the first layer. Influence of clamping location on gap size was also investigated.

Keywords: Gap formation, Finite element method (FEM), Multi-layered material

## 1 INTRODUCTION

In manufacturing, a variety of drilling methods are used for hole preparation in aerospace structures. The typical selection criteria and validation of drilling methods is through extensive laboratory testing and relies on: i. materials to be drilled, ii. hole quality requirements, iii. type of fasteners to be installed, iv. requirement of structural life cycle integrity and safety, v. expected drill hardware longevity, and many others. A major reason for relying on trial and error procedures is the lack of comprehensive understanding of drill performance and the interdependencies of cutting tools geometry, drill hardware, drill parameters, and drill methods. A typical large aircraft requires over 1.3 million holes to be prepared. In industry over 20% of manufacturing costs are directly tied to hole preparation and approximately 3 – 10 % of holes are reworked in production. The drilling process and hardware needs are often pushed toward the final stages of manufacturing and not considered in the up-front design and process planning

phases. The processes deployed to conform hole quality are often the source of discrepancies and require extensive rework as well as resources and time to fix deficiencies. These rework and process fixing activities typically cause a delay in schedule, cost overrun, and additional capital expenditures. An optimal engineering tool with process simulation capability will allow engineers to evaluate parameters in the process planning phase and reduce approximately 10 – 20 % laboratory time to validate processes for production. To a great extent these same challenges and opportunity exist in non-aerospace industry as well [1, 2].

In aircraft manufacturing, a multi-layered material consisting of several layers of different materials and sealant between the layers is used for the high strength-to-weight ratio of material that enables aircraft to carry more payload and/or fly farther with lower fuel consumption. Layers of materials are drilled simultaneously, but burr formation and chips migration between layers may require expensive deburring operations.

## 2 INTER-LAYER BURR AND GAP FORMATION

Typical inter-layer burrs are shown in Figure 1. They depend on the combination of the upper and the lower materials, the thickness of the sealant between layers and the process parameters. In general, as the drill moves downwards, a large exit burr forms at the exit surface of the upper material and a small entrance burr forms at the entrance surface of the lower material. When the sealant is thick enough, as in Figure 1(a), (b), and (c), the exit burr of the upper material is fully developed. If the upper material is ductile or the process conditions are in a specific range which results in a large uniform burr [3], the exit burr reaches to the top of the entrance burr, Figure 1(b), and sometimes it is deformed by hitting the entrance burr, Figure 1(c). Depending on the profile of the entrance burr and material properties such as hardness, the exit burr changes its growing path inwards, Figure 1(d), or in the worst case, outwards, Figure 1(c). When the sealant is thin, Figure 1(d), (e), and (f), the interference between the exit burr and the entrance burr occurs before the exit burr is fully developed.

Another important factor influencing an inter-layer burr is a gap formation between layers. If materials are different at each layer, their plastic and elastic behaviors are different and a discrepancy in deformations of the first and the second layer near hole induces a gap formation. Even for the same materials, the thickness of the first layer is changing during drilling process and again each layer will have different bending. The location and method of clamping the multi-layered workpiece also influence the gap formation. Engineers at Boeing have performed a series of tests to investigate the gap formation for various drill thrusts and clamp forces around a hole. Except the condition without a locked adjacent hole, results showed, Figure 2, that by applying a one-sided bushing clamp, the initial gap is significantly reduced initially and then decreases as bushing force increase.

Hence, many parameters such as drilling process parameters, material combination of layers, drill characteristics, clamping method, location and force, etc., influence the gap and inter-layer burr formation. Therefore, it requires much effort to conduct experimental investigation.

A finite element model is an economical way to investigate the gap formation and gives insight into inter-layer burr formation. Min [4] developed a 3-D finite element model of drilling burr formation for single-layered material. Based on his model, a finite element model of gap formation for multi-layered material was developed.

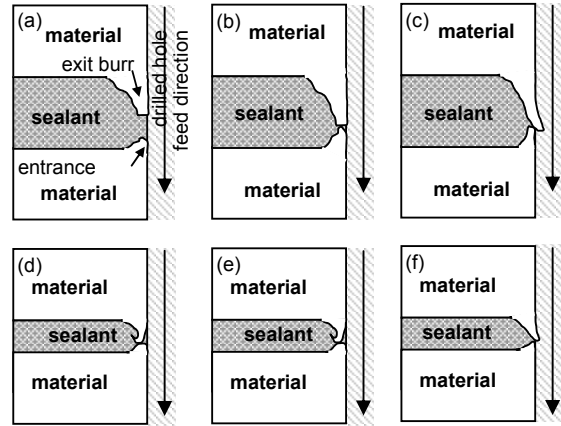


Figure 1: Inter-layer burrs in drilling a multi-layered material.

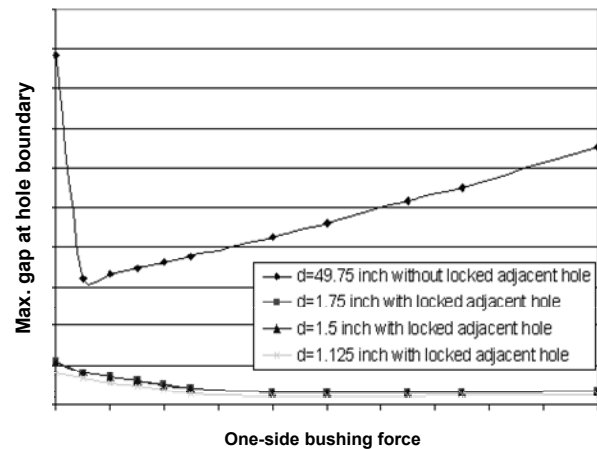
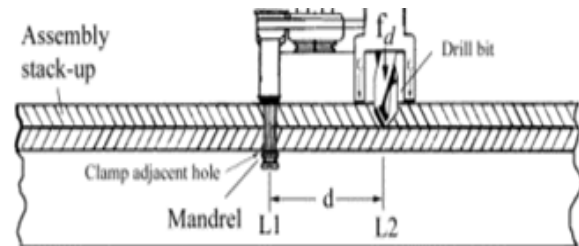


Figure 2: Schematic test setup and the maximum gap at different bushing forces.

### 3 3-D FINITE ELEMENT MODEL OF GAP FORMATION FOR A MULTI-LAYERED MATERIAL

#### 3.1 Modeling

A general purpose FEM software package, ABAQUS 6.3, is used to simulate the gap formation during drilling of a multi-layered material. Two layers of workpieces with the same material, stainless steel (AISI 304L) are used. For simplicity, the layers directly contact each other without a sealant. The thickness of each layer is 1.5 mm. Its material properties are listed in Table 1-4. Incremental plasticity using von Mises yield surface and associated flow rule are used to model the plastic behavior of the material. All material properties are assumed to be isotropic. The strain rate dependency of material properties is modeled using the overstress power law because material properties, especially yield stress, vary at high strain rate (strain rate in drilling typically ranges from  $10^3$  to  $10^5$ ). Hence, a material's yield stress,  $\bar{\sigma}$ , is dependent on work hardening, which for isotropic hardening models is usually represented by a suitable measure of equivalent plastic strain,  $\bar{\varepsilon}^{pl}$ , the inelastic strain rate,  $\dot{\bar{\varepsilon}}^{pl}$ , temperature,  $T$ , and predefined field variables,  $f_i$ ,

$$\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}^{pl}, \dot{\bar{\varepsilon}}^{pl}, T, f_i) \quad (2.1)$$

The overstress power law is represented by

$$\dot{\bar{\varepsilon}}^{pl} = D \left( \frac{\bar{\sigma}}{\sigma^o} - 1 \right)^n \quad \text{for } \bar{\sigma} \geq \sigma^o \quad (2.2)$$

Material failure was assumed to occur when the ratio of the incremental equivalent plastic strain to the equivalent plastic strain exceeds 1. Once an element satisfies this failure criterion, it becomes inactive in the remaining calculations [5].

A conventional 6mm diameter drill bit with point angle 130 degree and helix angle 40 degree is used for simulation. Drill bit is assumed to be perfectly rigid. In order to generate a FE model of the drill, software which creates a solid model of the drill and a FE mesh is developed. Feed and speed are 0.5mm/sec and 1200 rpm, respectively. The interaction between the drill bit surface and workpiece is modeled with contact mechanism with tangential friction behavior with friction coefficient of 0.3.

Temperature (°C)	25	100	450	850
Specific heat (J/MT)	450	500	525	550

Table 1: Temperature-dependent thermal properties of AISI 304L

Temperature (°C)	Young's modulus (GPa)	Poisson's ratio
25	193	0.3
150	181	0.31
260	172	0.32
370	164	0.33
480	156	0.34
600	146	0.34
700	139	0.35

Table 2: Temperature-dependent elastic properties of AISI 304L

Temperature (°C)	Plastic strain	Yield stress (MPa)
25	0	205
	0.16	721
150	0	157
	0.15	623
260	0	135
	0.14	554
370	0	123
	0.13	503
480	0	112
	0.12	483
600	0	101
	0.11	410
700	0	90
	0.10	300

Table 3: Temperature-dependent plastic properties of AISI 304L

Density (Kg/m <sup>3</sup> )	7800
Inelastic heat fraction	0.8
Strain rate dependency	D=1500, n=6

Table 4: Other properties of AISI 304L

Four clamps are located at the distance of 4.24mm from the center of the drilled hole. For modeling of the clamping, a fixed boundary condition is used on the external surfaces of both layers in the area where the clamp contacts the workpiece. Each contact area of the clamp is assumed to be a circular shape with diameter of 4 mm. A finite element mesh of the model is shown in Figure 3.

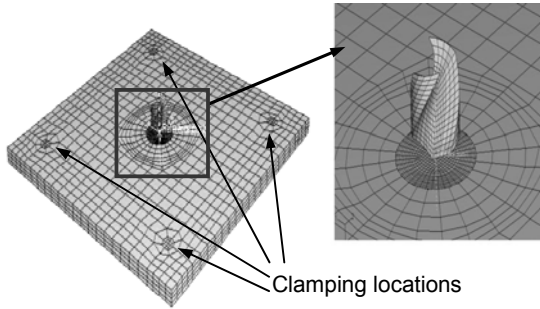


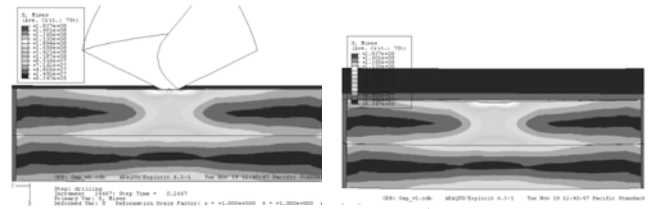
Figure 3: A finite element meshes of a two-layered workpiece and a drill.

### 3.2 Gap formation

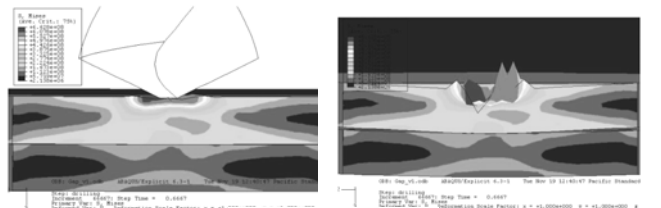
Figure 4 shows the process of the gap formation. The figures on the right are magnified 10 times in the drill feed direction. When the drill engages the first layer of the workpiece, a small area around the drill tip experiences plastic deformation and a very small elastic bending is initiated at the other area of the workpiece. Before the material fails due to the cutting of the drill, a very small gap is initiated due to the difference of elastic bending of each layer ( $t=0.27$  second), Figure 4(a). In this stage, no element deletion representing failure of the material occurs and only elastic bending of the workpiece is observed.

As the drill advances toward the exit surface of the first layer, the small gap between layers becomes larger. The thickness of the first layer in front of the drill tip decreases as the drill advances while the second layer maintains constant thickness. When the plastic deformation in front of the drill tip reaches the exit surface of the workpiece, the deformed material of the first layer pushes the second layer and the gap size increases dramatically ( $t=0.67$  second), Figure 4(b). In this stage, transition from cutting to bending starts and burr formation is initiated [4]. Figure 4(c) and (d) show further development of the gap formation, the drill advances the gap

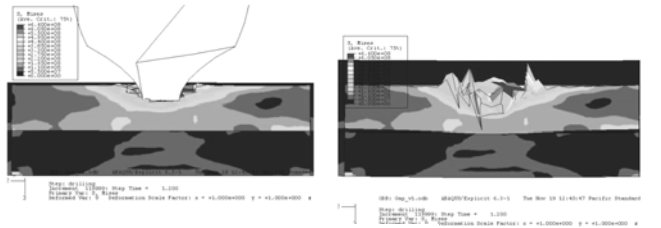
grows near the edges of the hole and also expands towards the clamping locations, Figure 4(e).



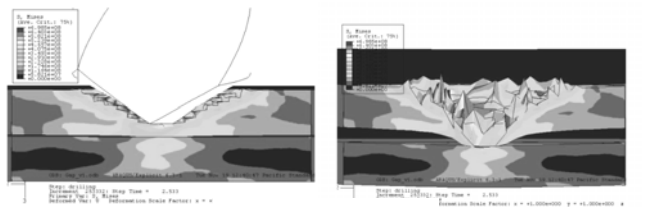
(a)  $T = 0.27$  sec



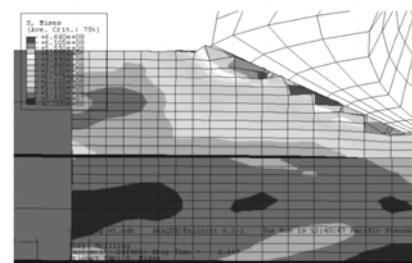
(b)  $T = 0.67$  sec



(c)  $T = 1.20$  sec



(d)  $T = 2.53$  sec



(e) Gap expands toward clamps

Figure 4: FE simulation of gap formation process.

Figure 5 shows the displacement of the node located 3 mm from the center of the hole (edge of the hole) on the exit surface of the first layer. The displacement of the node increases linearly up to 0.28 mm until the plastic region reaches the exit surface of the first layer (about 0.67 second). After this point, material in front of the drill tip experiences severe plastic deformation and failure. In the finite element simulation, failure of material is achieved by element elimination and creates a void in front the drill tip. Hence, a reverse force is created and the node under observation is moved back. This causes the oscillation of the displacement in the figure after 0.67 second. The moving average increases with time because the drill is pushing material toward the second layer.

Before the plastic deformation reaches the exit surface of the first layer, overall bending of the first and second layers is elastic and results in linear displacements with slight differences, which cause a very small gap formation as shown in Figure 6. When the plastic deformation starts at the center of the exit surface of the first layer and expands toward to the edge of the hole, the largely deformed first layer springs back due to yielding near edge of the hole while the elastically deformed second layer is supported by the center of the drilling position of the first layer, causing a large gap formation. As the drill advances, the gap grows as shown in the figure.

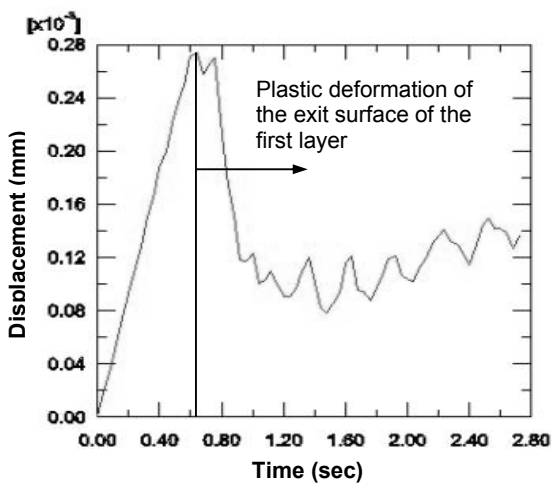


Figure 5: Displacement of the edge of the hole.

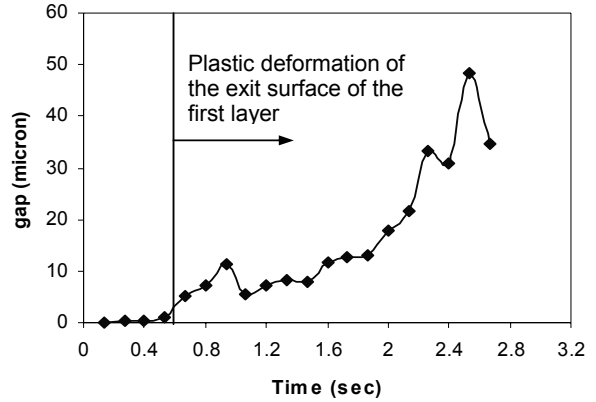


Figure 6: Displacement of the edge of the hole.

### 3.3 Effect of clamping location

Figure 7 and 8 show the maximum gap formation from FE simulations for different clamping locations. The maximum gap size varied little as clamping distance from the center of the hole increased. This can be explained by the elastic bending of the workpiece. Except near the hole, most parts of both layers of the workpiece experience only elastic bending throughout drilling process. Even though the displacement by elastic bending exponentially increases as the distance between clamping location and the center of the hole increases, as shown in Figure 9, displacements of both layers by this elastic bending would produce only a small discrepancy between layers which would have very little effect on the gap formation as illustrated in Figure 6. As explained in the previous section, the maximum gap size depends more on the value of plastic deformation at the center of the exit surface of the first layer. The value of plastic deformation highly depends on the thrust force exerted by the drill bit [6]. Hence, the maximum gap size depends on the thrust force exerted near the hole and the clamping location within 2x to 4x of diameter of the drill governs overall elastic bending.

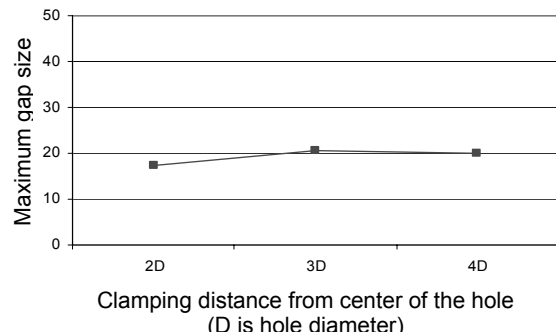


Figure 7: Gap size variation at different clamping location.

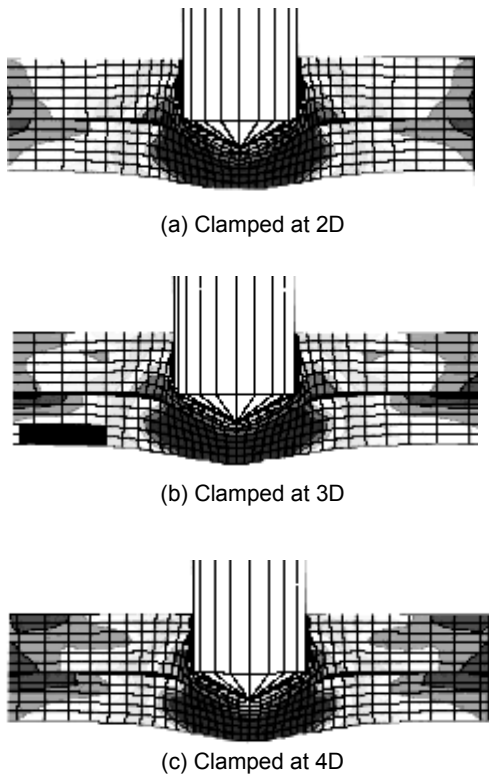


Figure 8: FE simulation of gap formation at different clamping location.

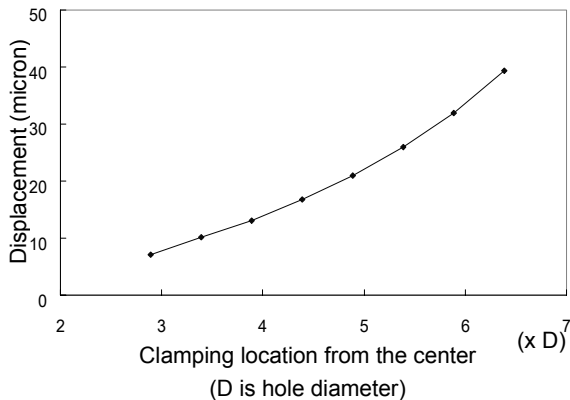


Figure 9: Displacement of the edge of the first layer at different clamping location.

#### 4 SUMMARY

Inter-layer gap formation in drilling of a multi-layered workpiece plays an important role in inter-layer burr formation. Understanding of inter-layer gap formation is required for aerospace applications. Hence, a finite element model for inter-layer gap formation in drilling of multi-layered

material was developed. From FE Analysis, the gap formation mechanism was proposed. A gap initially formed due to the discrepancy in elastic bending of layers. It slightly grew until the plastic region in front of the drill tip reached the exit surface of the first layer. As the plastic deformation expanded to the edge of the hole while the second layer was supported by the center of the first layer, the gap size increases dramatically.

Gap size variation for different clamping location was studied. FE analysis showed that the clamping location in a reasonable range governed only overall elastic bending of the layers and had little influence on the gap size while thrust force induced by process parameters such as feed and speed had great influence on the gap size.

More experimental verification requires taking full benefits of this FE model. This study intends to initiate more research on this area along with further development of the FE model.

#### 5 ACKNOWLEDGMENTS

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