EFFECT OF TOOL MATERIAL IN FRICTION DRILLING A CASE STUDY

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ABSTRACT

Friction drilling process is a rotating conical tool to penetrate the work piece and creates a bushing in a single step without generating chips. This work investigates the finite element modeling (FEM) of large plastic strain and high-temperature work-material deformation in friction drilling. The work-material deformation is very large, and both the tool and work piece temperatures are high in friction drilling. Modeling and Simulation is a necessary tool to understand the material flow, temperatures, stresses, and strains, which are difficult to measure experimentally during friction drilling. A semi empirical analytical model based on the contact pressure and temperature will be developed to predict the thrust force and torque in friction drilling. The FEM is used to analyse the large deformation of the work material in friction drilling. In this study, the DEFORM-3D software is used to simulate the behaviour of Friction Drilling Process and effect of tool material on shape of bushing formed is analysed.

KEYWORDS: Aluminium, Chipless Hole Making, Drilling, Deform-3D, Friction, Tungsten Carbide

INTRODUCTION

The idea of rubbing two materials together to produce heat is as old as people learning to make fire in the Stone Age. However, applying the principle to drilling holes in metal is a more recent development. Most people who have worked in machine shops have at one time or another tried to drill a hole with a very dull bit. The result is a lot of smoke and heat. Jan Claude de Valliere, working on a little farm in the south of France some seventy-five years ago encountered the same problem [1]. He recognized that if enough heat is generated he could melt and form a hole through the metal. With that thought in mind, he developed a special drill designed to increase friction. After many trials, he found a shape that worked. Friction drilling, also known as thermal drilling, flow drilling, form drilling, or friction stir drilling, is a non-traditional hole-making method. The heat generated from friction between a rotating conical tool and the work piece is used to soften the work-material and penetrate a hole.

The tip of the conical tool approaches and contacts the work piece. The tool tip, like the web center in twist drill, indents into the work piece in both the radial and axial directions. Friction on the contact surface, created from axial force and relative angular velocity between tool and work piece, produces heat and softens the work piece material as the tool is extruded into the work piece.[2-3] The tool moves further forward to push aside more work piece material and form the bushing[17-18] using the cylindrical part of the tool. As the process is completed, the shoulder of the Tool may contact the work piece to collar the back extruded burr on the bushing. Finally, the tool retracts and leaves a hole with a bushing on the work piece.

FRICITION DRILLING FEM

Mathematical formulations of thermal and mechanical modeling are presented in this section. [6]
Thermo Mechanical Fem Formulation

The friction and plastic deformation generate heat and elevate the workpiece temperature. The high temperature softens the workpiece and allows material to flow and form the hole and bushing. The governing equation for the thermal model is: \[ \rho c \frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + G \]

--Equation (1)

where \( \rho \) is the density, \( c \) is the specific heat, \( k \) is heat conductivity, \( T \) is the temperature, \( t \) is the time, \( G \) is the heat generation rate, and \( x, y, \) and \( z \) are spatial coordinate. The \( \rho, c, \) and \( k \) are functions of temperature, which is important for accurate thermal modeling. Both \( T \) and \( G \) are functions of \( x, y, z, \) and \( t \). The heat generation rate, \( G \), in friction drilling consist of the heating by the friction between tool and workpiece, \( q_f \) and heating from irreversible plastic deformation inside the workpiece:

\[ G = \dot{q}_f + \dot{q}_p \]

Equation (2)

This study assumes that friction between the tool and workpiece follows Coulomb’s friction law. The frictional force \( F_f \) is directly proportional to normal force, \( F_n \), by the coefficient of friction, \( \mu \) i.e., \( F_f = \mu F_n \). The frictional heat generation rate, is equal to \( F_f \) times the surface velocity of the tool (\( V \)). At the local contact point with tool radius, \( R \), \( V = 2\pi RN \), where \( N \) is the tool rotational speed. The frictional heat generation rate, \( q_f \) is

\[ \dot{q}_f = 2\pi RN \mu F_n \]

--Equation (3)

The heat generation rate can be formulated as:

\[ \dot{q}_p = \eta \sigma \dot{\varepsilon}^{pl} \]

- Equation (4)

Where \( \eta \) is the inelastic heat fraction, \( \sigma \) is the effective stress, and \( \dot{\varepsilon}^{pl} \) is the plastic straining rate [14]. Most of the elastic portion of the energy in large plastic deformation in the workpiece of friction drilling is small. In this study, \( \eta \) was set to 0.7 [8-9]

ANALYTICAL THRUST FORCE AND TORQUE MODEL

![Figure 1: Key Dimensions of the Friction Drilling Tool](image-url)
A model, based on the pressure and contact area between the tool and workpiece, is established to predict the thrust force and torque in friction drilling. Two elemental shapes the tapered cylinder and straight cylinder are used to model the contact area, as shown in Fig. 2. Tapered cylinder is defined by three parameters namely: two heights, h1 and h2, and an angle, \( \theta \). This angle \( \theta \) can be either \( \alpha \) or \( \beta \), depending upon the center or conical contact region of the tool Fig. 3 (b). A uniform pressure \( p \), which can be estimated by the yield stress of the rigid-plastic work-material at a given temperature, is acting on the surface. [7] Two coefficients of friction \( \mu \) and \( \mu_a \) are used to calculate forces in the radial and axial directions. In the radial direction, the workpiece is sliding on the fast rotating tool surface with surface speed of 1530 mm/s without lubricant. As work by friction stir welding [5], this results in a relatively high \( \mu \). In the axial direction, the tool is penetrating the workpiece at very slow speed of 4 mm/s. The \( \mu_a \) is expected to be lower than \( \mu \). Equations for thrust force and torque in the tapered cylinder area (Fig. 3 (a) with an inclusion angle \( \theta \) can be derived as:

\[
F = \int_{\alpha}^{\beta} p \sin \frac{\theta}{2} \, dA = \frac{p}{2} \left( h_1 \cos \frac{\theta}{2} - h_2 \cos \frac{\theta}{2} \right) \left( \tan \frac{\theta}{2} + \mu \right) \tan \frac{\theta}{2} \\
T = \int_{\alpha}^{\beta} \mu a p \, dA = \frac{2 \pi p \left( h_1^2 - h_2^2 \right) \tan \frac{\theta}{2}}{3 \cos \frac{\theta}{2}}
\]

Equation (6 & 7)

In the straight cylinder area, the thrust force and torque are:

\[
F = 2 \pi \mu_a p R h_3 \\
T = 2 \pi \mu a p R^2 h_3
\]

Equation (8 & 9)

Figure 2: Geometrical Relationship to Calculate H* the H*Can be Obtained from Fig (4) As:

Figure 3: (a) Tapered Cylinder (b) Straight
Two basic areas for contact between the tool and workpiece in friction. Cylinder The contact between the double angle friction drilling tool and the undeformed workpiece sheet are divided into six stages, as shown in Fig. 4. Which shows the geometrical illustrations of different overlapping area between the tool and workpiece during the six stages of friction drilling. [11] The distance of tool travel in the axial direction is during the six stages as follows:

\[ h^* = h_n \frac{\tan(\frac{\alpha}{2})}{\tan(\frac{\beta}{2})} - h_c \]  

-- Equation (10)

![Image](image1.png)

**Figure 4: Six Stages in Friction Drilling force Modeling.**

**FRICION DRILLING SIMULATION USING DEFORM-3D**

Fig (5) describes the 3D-Modal of Drilling tool and workpiece and also the elemental shape. [13]

![Image](image2.png)

**Figure 5: Initial Position of the Meshed Tool & Workpiece**

**Model Parameters and Materials used for Simulation of Friction Drilling**

Figure (6&7) shows the finite element meshed model of the tool and workpiece interface and boundary conditions. As shown in Fig the workpiece was 8 mm in diameter and 0.5 mm thick. The top surface of the workpiece is under free convection with convection coefficient of 30 W/m²·°C and ambient air temperature of 22°C.

**Object 1: Workpiece**

- Type: Plastic
- Mesh Elements: 6345, Nodes: 14333
- Material: Al 6061 Machining
- Diameter: 8mm, Thickness: 0.5mm
- Boundary Conditions: X, Y and Z Fixed

**Object 2: Tool**

- \( \alpha = 90^\circ, \beta = 30^\circ, h_n = 0.340 \text{mm}, \text{and} h_c = 5.118 \text{mm} \)
- Axial Feed Rate: 5.83 mm/sec,
- Tool Rotating Speed: 3000 rpm,
- Type: Rigid
- Primary axis
- Geometry: Polygons 4000, Points: 2000
- Mesh Elements: 38183, Nodes: 8299
- Material: WC (Tungsten carbide)
The tool speed is set to 3000 rpm or 314 rad/s. The tool penetration rates are modeled for three different axial feeds and they are: 2.54, 4.23, and 5.93 mm/s into the work piece the movement of work piece is arrested in all X, Y and Z directions. The geometric parameters of the tool used in this study from [1-3]. Aluminum alloy 6061 was chosen as the work-material and Tool as WC (Tungsten carbide). Material properties of both work piece and tool are listed in Table No. (1) and (2) [4]

### Material Properties for Tool & Work Piece

Table 1: Listed the workpiece and Table 2: Presents the tool Properties

#### Table 1: Material Properties for work Piece Aluminum 6061 [15]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity(W/m°C)</td>
<td>162</td>
</tr>
<tr>
<td>Heat Capacity(J/Kg °C)</td>
<td>945</td>
</tr>
<tr>
<td>Density(Kg/m³)</td>
<td>2690</td>
</tr>
<tr>
<td>Young’s Modulus(Gpa)</td>
<td>68.5</td>
</tr>
<tr>
<td>Yield Strength(Mpa)</td>
<td>274</td>
</tr>
<tr>
<td>Thermal Expansion(1/°C)*10⁻⁶</td>
<td>23.5</td>
</tr>
</tbody>
</table>

#### Table 2: Material Properties for AISI 4340 and for Tungsten Carbide (WC)

<table>
<thead>
<tr>
<th>Property</th>
<th>AISI 4340</th>
<th>Tungsten Carbide (WC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (lb / cu. in.)</td>
<td>0.28</td>
<td>WC</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>7.8</td>
<td>Molecular formula</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>0.116</td>
<td>Molar mass(g/mol)</td>
</tr>
<tr>
<td>Melting Point (Deg F)</td>
<td>2600</td>
<td>Appearance</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>21</td>
<td>Grey-black lustrous solid</td>
</tr>
<tr>
<td>MeanCoeffThermal Expansion</td>
<td>6.6</td>
<td>Density(g/cm³)</td>
</tr>
<tr>
<td>Modulus of Elasticity Tension</td>
<td>33</td>
<td>15.63</td>
</tr>
<tr>
<td>Boiling point(°C/K/°F)</td>
<td>2870, 3143, 5198</td>
<td></td>
</tr>
<tr>
<td>Thermal Conductivity(°C/°K/°F)</td>
<td>6000 °C</td>
<td></td>
</tr>
</tbody>
</table>

#### SIMULATION OF FRICTION DRILLING PROCESS USING DEFORM-3D

This study is concerned with finite element simulation of friction drilling with WC and AISI4340 Tools. AL6061 aluminum [16] is machined with both the tools. 3D friction drilling operation is simulated and analyzed using FEM code DEFORM 3D. The distribution of effective stress, effective strain and formation of bushing in the friction drilling is studied. Finite element simulations were carried out for different feed rates and keeping speed constant with DEFORM-3D. Table 3 shows the different feed rates under which simulations were carried out. From the simulations, variables like
stresses, strains, total forces, velocities temperature distribution can be obtained. However, these are all very difficult to measure experimentally. [6-9]

**Effect of Drill Material on Shape of Bushing**

The shape of bushing and the depth of the hole are two important but difficult to quantify criteria in evaluating the quality in friction drilling. The observations of the bushing shape, based on cylindricality, petal formation, depth, and roughness, were made to judge the success of the friction drilled hole [3]. The bushing shape from friction drilling of AISI 4340 at different speeds is studied. The view of bushing from bottom of the work piece and a cross section view of the same hole are shown to reveal and compare different features of the hole and bushing. Shows the bushing formed in AL6061 for both the cases of drill materials AISI4340 and WC (Tungsten carbide) at 3000,3500 and 4000 rpm spindle speeds.

A significant change in bushing shape is noticed by varying the spindle speed and feed rates. Although the energy and power were reduced at high spindle speed, the bushing shape is still poor at the highest spindle speed. Significant petal formation and cracking are observed in each of the hole. The Spindle speed has a negative effect on the shape of bushing for WC then AISI4340. As shown in Fig. (8) & (9), as the spindle speed increases from 3000 to 4000 rpm, the petal formation becomes more apparent.

The views of bushing from top and bottom of the work piece and a cross section view of the same hole are shown to reveal and compare different features of the hole and bushing.

![Figure 8: The Shape of Bushing at 3000 rpm with Different Federates](image-url)
Effect of Tool Material in Friction Drilling a Case Study

Effect of Increasing of Feed rate on the effective-stress effective strain:

The effective-stress and effective strain at various speeds 3000, 3500, and 4000 rpm, feed rates 2.54, 4.23, and 5.93 mm/sec are studied and analyzed as shown in Table 3. Results for effective stress, effective strain and velocity by varying the feed rates [12-13]

Table: 3 Stress-Strain Model Values

<table>
<thead>
<tr>
<th>S.N</th>
<th>Speed (rpm)</th>
<th>Feed Rate (mm/sec)</th>
<th>For Material WC Effective stress(M pa)</th>
<th>For Material WC Effective strain</th>
<th>For Material AISI 4340 Effective stress (M pa)</th>
<th>For Material AISI 4340 Effective strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3000</td>
<td>2.54</td>
<td>1290</td>
<td>1.4</td>
<td>1400</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>3000</td>
<td>4.23</td>
<td>1050</td>
<td>6.8</td>
<td>1120</td>
<td>5.9</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>5.93</td>
<td>972</td>
<td>9.2</td>
<td>1060</td>
<td>7.2</td>
</tr>
<tr>
<td>4</td>
<td>3500</td>
<td>2.54</td>
<td>1240</td>
<td>1.9</td>
<td>1080</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>3500</td>
<td>4.23</td>
<td>1120</td>
<td>8.2</td>
<td>1170</td>
<td>8.5</td>
</tr>
<tr>
<td>6</td>
<td>3500</td>
<td>5.93</td>
<td>1050</td>
<td>9.1</td>
<td>1180</td>
<td>4.6</td>
</tr>
<tr>
<td>7</td>
<td>4000</td>
<td>2.54</td>
<td>1580</td>
<td>2.8</td>
<td>1200</td>
<td>2.4</td>
</tr>
<tr>
<td>8</td>
<td>4000</td>
<td>4.23</td>
<td>1340</td>
<td>8.1</td>
<td>1060</td>
<td>3.4</td>
</tr>
<tr>
<td>9</td>
<td>4000</td>
<td>5.93</td>
<td>1100</td>
<td>3.7</td>
<td>1030</td>
<td>3.2</td>
</tr>
</tbody>
</table>

The graphs between Effective Stress vs. Feed rate, Effective strain vs. Feed rate are shown in figure 10 & 11 for tool materials AISI 4340 and WC. From the Analysis it can be concluded that the stresses developed during the process for same feed and speed are more in AISI 4340 than WC
CONCLUSIONS AND FUTURE WORK

For AISI4340 and WC, the shape and quality of bushing were observed. Less severe cracking and petal formation were observed on bushings. For room temperature AISI 4340, high spindle speed was detrimental on the bushing shape. Higher feed rate and shorter cycle time for hole drilling was feasible with the reduced thrust force and torque. Fig.10&11 shows that with increase in feed and speed the Effective Stress in friction Drilling decreases. The increase of speed from 3000 rpm to 4000 rpm resulted in improper bush shape on the work piece. The simulation of the friction drilling process development of speed, feed rate as well as predictions of the stress distributions and strain distribution and bushing shape is successfully achieved by using DEFORM-3D.

This work has identified the need for future studies in following areas.

1. The FEM modeling can be extended to study the temperature and stress in the tool during friction drilling. This can be beneficial for the tool geometry design and tool material selection. A better tool geometry can also help to reduce the thrust force and deflection and improve bushing formation in the workpiece.

2. A more comprehensive friction model depending on the temperature and pressure needs further investigation.

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