An improved drilling force model in friction drilling AISI 321

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Abstract. In this paper, the friction characteristics and the drilling force theory model have been studied in friction drilling austenitic stainless steel AISI 321 for solving the drilling difficult problem of thin sheet workpiece. Firstly, a equivalent test platform of friction drilling friction characteristics is established based on CA6140 lathe, and the friction characteristics of AISI 321 are studied under the different conditions of contact pressure and speed for revealing the effect of pressure and speed on the friction coefficient between tool and workpiece. Then, the empirical formula model of friction coefficient is established based on the experimental results. Finally, the improved drilling force theory model of friction drilling process is developed based on the unique geometrical shape of friction drilling tool and the equivalent friction model. Results show that the predicted force model is more accurate, which considered the actual friction coefficient model.

1. Introduction
Drilling is one of the important process in manufacturing field [1]. Friction drilling is a non-traditional drilling method, commonly used in drilling processing of pipe or sheet type workpiece, which has been widely used in the automotive industry, aerospace engineering, lighting industry, metal construction, electroplating coating, Medical and fitness equipment and many other industries [2-4].

Austenitic stainless steel has the characteristics of high toughness and low thermal conductivity. However, these characteristics cause great difficulty in drilling processes. Thus, the most important task of drilling stainless steel is to improve the geometric shape of a drill and develop a new type of drilling process. Thermal friction drilling technology has become a solution to drill stainless steel. A new type of thermal friction drill with a sintered carbide was developed in which it can be grinded and processed to the necessary geometric shape [5]. Results indicated that the friction drill has a better performance than WC twist drill, and a good quality hole surface could be obtained. The relationship between drill surface temperature, tool wear and axial thrust force in friction drilling AISI 304 stainless steel by tungsten carbide drills with and without coating was investigated. It was found that AlCrN-coated drill produced the highest surface temperature but the lowest axial thrust force with the least tool wear; there have two types of tool wear of abrasive wear and the diffusion wear [6,7]. Friction drilling of hot rolled S235 steel and AISI 4301 stainless steel were carried out by Krasauskas et al. [8]. Results showed that the drilling force reaches the maximum value at the time when the tool cone penetrates the workpiece, gradually decreases after penetrating the workpiece, but the torque reaches the maximum value. Two models of friction drilling were developed for friction drilling, which built the foundation for friction drilling process optimization [9]. In the new theoretical model, the shear strength and the friction coefficient can be calculated from experimentally measured values of the instantaneous thrust force and torque [10]. The surface quality in friction drilling have been
studied [11-13]. Taguchi method was used to optimize the machining process of the thermal friction drilling stainless steel plate. The effects of friction angles, friction contact area ratio, feed rate, and spindle speed on the surface roughness were also investigated [12, 13]. Three-dimensional finite element model of friction drilling process were built by Gök, K et al [14]. Besides, friction drilling of the different materials, especially difficult-to-cut materials, which need different design of the drill tool.

In this paper, the friction characteristics of AISI 321 are studied based on CA6140 lathe under the different conditions of contact pressure and speed. Then, an equivalent friction coefficient model in friction drilling is developed based on the experimental results. Finally, an improved theoretical model of the drilling force in friction drilling is developed, which lays the foundation for the optimization of the tools.

2. Experimental Setup

For studying friction characteristics in friction drilling, an equivalent friction process is developed based on a friction contact pair, that is, a rotation of cylindrical workpiece and a grinding tool (seen in figure 1). The friction process is simulated by the movement between the cylindrical surface and the tool plane.

![Figure 1. Equivalent friction process principle.](image)

The workpiece is a cylindrical ring with the diameter of 110mm, the thickness of 10mm, and its material is AISI 321. The tool is carbide P10 with a cuboid of 10mm×10mm×100mm.

The friction characteristics test platform is built on the CA6140 lathe, which is shown in figure 2. Figure 2 (a) shows the friction test setup. The tool is fixed on three component piezoelectric turning dynamometer, which is fixed to the tool holder by bolts. The test data acquisition system converts the force signal into an electrical signal, which is transmitted to the data acquisition card through the data line and connected to the computer.

![Figure 2. Friction characteristics test platform(CA6140 lathe).](image)

3. Friction model

Table 1 shows the effect of normal pressure on the friction coefficient in friction test of AISI 321 under the velocity of 86.4m/min. It can be seen that the friction coefficient of AISI 321 increases when the normal force increases. Because the elongation of AISI 321 is about 60%, the friction coefficient between tool and workpiece increases due to the high plasticity.

The contact pressure is used in predicted force model, so the relationship between the friction coefficient and contact pressure should be obtained. It is assumed that the contact area is the same under the same normal force and the contact area between the tool and the workpiece under different conditions is calculated by contact area ratio.
normal force is measured by the way of imprinting under static conditions. Table 2 shows the results of contact area.

Table 1. Friction coefficient of AISI 321.

| Normal force (N) | 378.25 | 466.58 | 531.83 |
|------------------|--------|--------|--------|
| Coefficient      | 0.38   | 0.47   | 0.52   |

Table 2. Contact area of AISI 321 under different normal force.

| Normal force (N) | 200  | 300  | 400  | 500  |
|------------------|------|------|------|------|
| Contact area (mm²) | 1.8  | 2.0  | 2.2  | 2.3  |

The contact pressure $p$ can be given by:

$$ p = \frac{F}{A} \quad (1) $$

where $p$ is contact pressure, $F$ is normal pressure force, $A$ is the contact area.

Considering the influence of pressure and velocity on the friction coefficient, the empirical formula of the friction coefficient of AISI 321 is obtained by using multiple linear regression method, which is given by:

$$ \mu = 6.53 \times 10^{-4} p^{1.0894} v^{0.0936} \quad (2) $$

where $\mu$ is friction coefficient, $v$ is the velocity.

The empirical formula of the friction coefficient of AISI 1020 also can be obtained by:

$$ \mu = 1.081 p^{-0.0906} v^{-0.1254} \quad (3) $$

4. Friction force model

4.1. Friction drilling process

Thermal friction drilling tool has no cutting edge, the geometrical features of the friction drill are shown in figure 3. According to its geometric features, the tool can be divided into five parts: shank region, shoulder region, cylindrical region, conical region and center region.

Friction drilling process is a plastic deformation process of the workpiece. Firstly, the high-speed friction of the tool causes the thermoplastic deformation state of workpiece. Then, a pit is formed on the workpiece and gradually increases when the tool feeds. Finally, the workpiece is penetrated to form a smooth surface hole.

4.2. Drilling force model

In friction drilling process, the tool geometry in the machining changes when the tool feed, and the temperature between workpiece and tool is also variable. Here, the pressure $p$ of the workpiece is equivalent to the yield strength. Temperature has a great influence on the yield strength of workpiece.
material, and yield strength also has a great influence on the friction coefficient \( \mu \). Thus, the two variables of \( p \) and \( \mu \) should be considered in development of the friction force model. There are two types of contact geometries involved in the drilling process: conical and cylindrical. So the predicted force model can also be equivalent to two parts. The thrust force \( F \) and torque \( T \) in conical part can be expressed by [10]:

\[
F = \pi p \tan \left( \frac{\theta}{2} \right) \left( h_2^2 - h_1^2 \right) + 2\pi \mu p \frac{v}{\omega} \cos \left( \frac{\theta}{2} \right) \left( h_2 - h_1 \right)
\]  

(4)

where \( h_1 \) is the distance from the lower edge of the contact, \( h_2 \) is the distance from the upper edge of the contact, \( \theta \) is the inclusion angle of the cone, \( \omega \) is angular velocity.

\[
T = \pi \mu p \frac{2\tan \left( \frac{\theta}{2} \right)}{\cos \left( \frac{\theta}{2} \right)} \left( h_1^2 - h_2^2 \right) - \frac{v^2}{\omega^2} \pi \mu p \cos \left( \frac{\theta}{2} \right) \left( h_2 - h_1 \right)
\]

(5)

For a cylindrical part, the thrust force and torque thrust force \( F \) and torque \( T \) can be expressed by:

\[
F = 2\pi R h_1 \mu p \sin \gamma = \frac{2\pi \mu p R h_1 v}{\sqrt{v^2 + \omega^2 R^2}}
\]

(6)

where \( h_1 \) is the contact height, \( R \) is the radius in cylindrical part.

\[
T = 2\pi R^2 h_1 \mu p \cos \gamma = \frac{2\pi \mu p R^2 h_1 \omega}{\sqrt{v^2 + \omega^2 R^2}}
\]

(7)

The friction drilling process typically contains six stages[9,10], so the drilling force model also can be given by each stage.

4.3. Application of the model

To demonstrate the predicted model, AISI 1020 was used and the dimensions of the friction drill is \( d=7.3 \) mm, \( \alpha=90^\circ \), \( \beta=36^\circ \), \( h_1=0.970 \) mm, \( h_2=8.248 \) mm, \( h_1=8.896 \) mm, \( t=1.2 \) mm [9]. The drilling conditions is \( v=2.75 \) mm/s and \( \omega=418.67 \) rad/s.

The yield strength of AISI 1020 steel at room temperature is about 355MPa, which is affected by temperature. Considered the effect of temperature, \( p \) is given by:

\[
p = K_t \sigma_e
\]

(8)

\[
K_t = -2.022 \times 10^{-9} T^4 + 1.186 \times 10^{-4} T^2 - 9.808 \times 10^{-1} T + 0.980
\]

(9)

where \( K_t \) is the material coefficient related to temperature, \( \sigma_e \) is the yield strength of AISI 1020 steel at room temperature.

Table 3 show the temperature of workpiece in friction drilling AISI 1020. Figure 4 shows the predicted thrust force by the improved model, which considered the variables of \( p \) and \( \mu \). It can be seen that when the coefficient of friction is set as a variable, the maximum value of the thrust force is in stage 3, which is closer to the experimental results (seen in figure 5). Therefore, the improved drilling force model is effective, which can be used to predict the thrust force and torque.

**Figure 4.** Predicted thrust force by the improve mode.
Table 3. Temperature of workpiece in friction drilling AISI 1020.

| Feed (mm) | 0.055 | 2.2 | 4.4 | 8.8 | 11.55 | 13.75 | 15.95 |
|-----------|-------|-----|-----|-----|-------|-------|-------|
| Temperature (°C) | 240 | 640 | 700 | 760 | 680 | 480 | 300 |

Figure 5. Predicted thrust force in Ref [9].

Under the same conditions, the predicted friction forces of AISI 321 are shown in figure 6. Results indicate that thrust force increases rapidly and reaches the maximum value in the third stage, when the tool has just penetrated the workpiece; then, the thrust force decreases slowly in the fourth stage and decreases rapidly in the fifth stage; the torque increases firstly then decreases, and the maximum value is in the fourth stage. Because the drilling temperature is not high enough at the initial stage and the yield strength is high. The mechanical energy of the friction is converted into heat energy with the friction processing, the yield strength decreases when the temperature increases, so the thrust force decreases. As the tool feed increases, radius of the tool increases, that is, the main reason for the increase of the torque.

Figure 6. Predicted friction force in drilling AISI 321.

5. Conclusions
A improved model of friction drilling has been developed based on earlier studies [9, 10], which useful for predicting the thrust force and torque. The new approach is more fundamental than the previous model that assumed certain values for the friction coefficient, which considers temperature-dependent contact pressure and variable friction coefficient. According to the analyses above, we have the following points:
(1) The equivalent test method for friction characteristic of friction drilling was established. Based on this, the empirical formula model of friction coefficient was developed, which laid the foundation for predicting force model.

(2) The improved force model of friction drilling was developed, which considered the changes in temperature, pressure and friction coefficient. Results showed that the improved model was more accurate, which was more consistent with the experimental results.

(3) The improved force model is more accurate, which laid the foundation for selecting suitable tool feed rate and tool geometry.

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References
[1] Wu J, Wen J M and Wang Z Y 2016 Study on the predicted model and experiment of drilling forces in drilling Ti-6Al-4V Journal of the Brazilian Society of Mechanical Sciences and Engineering 38(2) 1-8
[2] Miller S F, Blau P J and Shih A J 2007 Microstructural Alterations Associated With Friction Drilling of Steel, Aluminum, and Titanium Journal of Materials Engineering and Performance 14 647-653
[3] Pramanik A, Zhang L C and Arsecularatne J A 2007 An FEM investigation into the behavior of metal matrix composites: Too-particle interaction during orthogonal cutting International Journal of Machine Tools & Manufacture 47 1497-1506
[4] Issaa M, Labergera C, Saanounia K And Rassineux A 2012 Numerical prediction of thermomechanical field localization in orthogonal cutting CIRP Journal of Manufacturing Science and Technology 5(3) 175-195
[5] Chow H M, Lee S M and Yang L D 2008 Machining characteristic study of friction drilling on AISI 304 stainless steel Journal of materials processing technology 207 180-186
[6] Lee S M, Chow H M, Huang F Y and Yan B H 2009 Friction drilling of austenitic stainless steel by uncoated and PVD AlCrN- and TiAlN-coated tungsten carbide tools International Journal of Machine Tools & Manufacture 49 81-88
[7] Miller S F, Blau J and Shih A J 2007 Tool wear in friction drilling,” International Journal of Machine Tools & Manufacture 471636-1645
[8] Krasauskas P 2011 Experimental and statistical investigation of thermo- mechanical friction drilling process MECHANlKA 17(6) 681-686
[9] Miller S F, Li R, Wang H and Shih A J 2006 Experimental and Numerical Analysis of the Friction Drilling Process Journal of Manufacturing Science and Engineering 128 802-810
[10] Qu J and Blau P J 2008 A New Model to Calculate Friction Coefficients and Shear Stresses in Thermal Drilling Journal of Manufacturing Science and Engineering 130 1-4
[11] Lee S M, Chow H M and Yan B H 2007 Friction Drilling of IN-713LC Cast Superalloy Materials and Manufacturing Processes 22(7-8) 893-897
[12] Ku W L, Sheu T S, Chow H M, Lee S M, Yang L D and Lin Y C 2008 Optimization of Machining Parameters of a Novel Friction Drilling Process Journal of materials processing technology 207 180-186
[13] Ku W L, Hung C L, Lee S M and Chow H M 2011 Optimization in thermal friction drilling for SUS 304 stainless steel Int J Adv Manuf Technol 53(9-12) 935-944
[14] Gök K, Gök A and Bilgin M B 2017 Three-dimensional finite element model of friction drilling process in hot forming processes Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering 231(3) 548-554