Finite element simulations of rail milling based on the modified Johnson-Cook constitutive model

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Abstract: Rail milling plays an indispensable role to remove surface defects and irregularity in the railway maintenance industry. In this paper, an appropriate 2D orthogonal cutting model of rail milling process was established. Finite element simulations of rail milling were conducted in detail based on a modified Johnson-Cook constitutive model. The simulation results show that a large amount of cutting heat is generated in the tool-chip contact region, and the highest temperature of the milling insert appears somewhere on the rake face with a certain distance away from the cutting edge. With the increase of cutting thickness and milling speed, the milling temperature displays an upward trend.

1. Introduction
Rail is one of the extraordinarily significant infrastructures in the railway network, which directly impacts the smooth and safe operation of trains. With the rapid development of railway network throughout the world, the train speed becomes faster and the axle load becomes heavier, thus more defects are generated under the intricate wheel/rail contact conditions, such as rolling contact fatigue cracks [1], spalling [2] and squats [3]. To guarantee the safety and stability of railway network, it is crucial to adopt rail maintenance technologies to effectively eliminate the surface defects and unevenness, which can be divided into rail grinding and rail milling. Compared with rail grinding, rail milling technology is a kind of a rather new application in the rail maintenance field, which is originated from LINSINGER company in Austria. During the process of rail milling, a combined milling cutter with the milling inserts distributed along its circumferential surface is utilized to perfectly cover the profile of rail head, which can efficiently eradicate the surface flaws and irregularity in only one pass. In addition, rail milling possesses the advantages of free of sparks, environmentally-friendly and high machining precision.

Up to date, many finite element researches on the milling process of composites, aluminum and other alloys can be available [4-6], however, there are very few finite element simulations addressing the rail milling process, which reveals that there is a lack of adequate research on the finite element modeling of rail milling process. Performing rail milling simulations is conducive to get a better understanding of the extremely complex metal cutting process.

In this paper, firstly, a 2D orthogonal cutting model of rail milling process is established by simplifying the 3D rail peripheral milling process equivalently and reasonably. Then, the finite element simulations are carried out on the basis of a modified Johnson-Cook constitutive model. Finally, based on the simulation results, the temperature distribution and the chip formation process are discussed in detail.
2. Establishment of finite element model

2.1. Conversion of 3D rail peripheral milling process to 2D orthogonal cutting

Currently, 2D orthogonal cutting finite element simulation is widely adopted for the analysis of machining process. The conversion of 3D rail peripheral milling process to 2D orthogonal cutting can effectively reduce the element numbers and improve the simulation efficiency. During the down milling process, the cutting thickness constantly shifts, the cutting area of a milling insert is the area enclosed by the motion trajectories of two adjacent milling inserts. Although the cutting thickness changes continuously, due to the high speed of the milling cutter and the very small feed per tooth, the change in the cutting thickness is also extremely small, therefore, the continuously changing cutting thickness can be regarded as equivalent uniform cutting thickness \( h_e \), the conversion of 3D rail peripheral milling process to 2D orthogonal cutting is shown in Figure 1. The equivalent uniform cutting thickness \( h_e \) is calculated as

\[
h_e = r - \frac{1}{\sqrt{r^2 - 2 \frac{A_c}{K_c}}} = r - \frac{\arccos \left( \frac{f_z}{2r} \right) - \arcsin \left( 2 \cos \left( \frac{f_z}{2r} \right) \right)}{\pi - \arccos \left( \frac{f_z}{2r} \right)}
\]

(1)

where \( f_z \) and \( r \) represent feed per tooth and the radius of the milling cutter, respectively. \( K_c \) and \( A_c \) indicate the contact angle and the cutting area, respectively, which can be calculated as

\[
K_c = \pi - \arccos \left( \frac{f_z}{2r} \right)
\]

(2)

\[
A_c = \frac{1}{2} r^2 \left[ \pi - \arccos \left( \frac{f_z}{2r} \right) + \sin \left( 2 \cos \left( \frac{f_z}{2r} \right) \right) \right]
\]

(3)

It can be found form Equation (1) that the equivalent uniform cutting thickness \( h_e \) is the function of the radius of the milling cutter and feed per tooth, when the radius of the milling cutter remains constant, \( h_e \) is only related to feed per tooth \( f_z \).

![Figure 1](image.png)

Figure 1 Conversion of 3D rail peripheral milling process to 2D orthogonal cutting

ABAQUS/Explicit in the commercial finite element simulation software ABAQUS™ 6.14 is engaged to establish 2D orthogonal finite element model of rail milling. CPE4RT four-node plane strain thermal-mechanical coupling element is used to perform mesh division for the workpiece and the cutting tool. The cutting tool is set as an ideal rigid body, and the workpiece is set as a plastic body. Mesh refinement is performed in the tool/workpiece contact area, while the non-contact area is divided by relatively sparse meshes. The horizontal displacement of the left nodes and the horizontal and vertical
displacement of the bottom nodes of the workpiece are constrained, while the horizontal displacement and any rotational movement of the cutting tool are restricted. The established 2D orthogonal cutting finite element model is presented in Figure 2. The rake angle and clearance angle are -8° and 8°, respectively. In this study, the workpiece is U71Mn rail material made from high carbon steel to possess high fatigue toughness, which is extensively engaged in current Chinese railway network [7]. The chemical compositions of the studied material are listed in Table 1. In order to avoid serious mesh distortion which can result in difficulty in convergence, arbitrary Lagrange-Euler (ALE) and adaptive mesh technique are adopted. During the simulation, the cutting tool moves at the milling speed \( v_c \), while the workpiece is fixed. The initial ambient temperature is set as 25°C. The heat transfer coefficient between the workpiece material and the tool is set as \( 10^{5} \text{ W} \cdot \text{m}^{-2} \cdot \text{°C}^{-1} \).

\[ \begin{align*}
\sigma &= 1231.54 + 2501.96e^{1.587} \left[ 1 + 0.01284 \ln \left( \frac{\varepsilon}{0.001} \right) \right] \left[ 1 - 1.27 \left( \frac{T - 20}{1449} \right) \right]^{-0.85624} \left( -0.48T + 361.8 \right) \\
&= (4)
\end{align*} \]

where \( \sigma \) represents von Mises stress; \( \varepsilon \) is the plastic strain; \( \dot{\varepsilon} \) is the true strain rate; \( T \) indicates the experimental temperature.

The room-temperature physical properties of U71Mn rail material and the milling insert (Chinese brand: YC30S) are listed in Table 2. The temperature-dependent thermo-physical properties of U71Mn rail material and the milling insert are given in Table 3 and Table 4, respectively.

| Material | C     | Mn    | Si     | S     | P     | Fe     |
|----------|-------|-------|--------|-------|-------|--------|
| U71Mn    | 0.65-0.76 | 0.70-1.20 | 0.15-0.58 | ≤0.025 | ≤0.030 | Balance |

2.2. Material parameters

According to [7], a modified Johnson-Cook constitutive model of U71Mn rail material is utilized via VUMAT user material subroutine, which is expressed as

\[ \begin{align*}
\sigma &= 1231.54 + 2501.96e^{1.587} \left[ 1 + 0.01284 \ln \left( \frac{\varepsilon}{0.001} \right) \right] \left[ 1 - 1.27 \left( \frac{T - 20}{1449} \right) \right]^{-0.85624} \left( -0.48T + 361.8 \right) \\
&= (4)
\end{align*} \]

Table 1 Chemical compositions of U71Mn rail material (wt.%)
Specific heat capacity (J·kg⁻¹·°C⁻¹) | 508 | 526 | 544 | 586 | 669 | 721 | 827 | 732
---|---|---|---|---|---|---|---|---
Heat conductivity (W·m⁻¹·°C⁻¹) | 65.12 | 68.43 | 72.01 | 75.66 | 79.31 | 82.97 | 86.71 | 90.62
Specific heat capacity (J·kg⁻¹·°C⁻¹) | 240 | 249 | 263 | 278 | 293 | 315 | 334 | 359

2.3. Tool-chip friction model
The highly versatile modified Coulomb friction model is taken as the tool-chip contact model. During the cutting process, the tool-chip contact region is composed of two parts, namely the slip zone and the stick zone. The chip stick-slip feature along the tool-chip interface relies on the normal stress between tool/chip surfaces. The modified Coulomb friction model used in the simulation is formulated as [8]

$$\tau_f = \begin{cases} \mu \sigma_n, & \tau_f < \tau_y \\ \tau_y, & \tau_f \geq \tau_y \end{cases}$$

(5)

where $\tau_f$ is the frictional stress; $\tau_y$ and $\sigma_n$ are the shear yielding stress and normal stress, respectively; $\mu$ is the coefficient of coulomb friction.

Professor T. Altan, a well-known expert in numerical analysis from Ohio State University, pointed out that when the friction coefficient is set as 0.6, high calculation accuracy can be obtained for finite element simulation under multiple materials and multiple changing parameters [9]. Therefore, $\mu=0.6$ is applied in the study, and $\tau_y=711.03$ MPa.

2.4. Damage model
Cockroft-Latham criterion is adopted as the failure or damage model of the studied material, which is formulated as [10]

$$C = \int_0^\varepsilon^p \sigma d\varepsilon^p$$

(6)

where $\varepsilon^p$ is the equivalent plastic strain when the material fractures, $C=481.98$MPa is adopted in this study.

3. Results and discussion

3.1. Chip formation and temperature distribution analysis
When the milling speed $v_c=200$ m/min, the strip chip formation process and temperature distribution are shown in Figure 3. At the beginning of milling process, tower-like shape is formed at the chip top, and the temperature gradient in the first deformation zone is large. As the milling process proceeds, the cutting temperature continues to rise, and the cutting material is strongly squeezed and sheared by the cutting tool, during which the new machined surface is formed. Due to the strong extrusion and friction effects between the chip and the tool, a large amount of cutting heat is generated in the tool-chip contact area, which causes the temperature of the contact area to rise rapidly. The maximum temperature of the cutting tool appears somewhere on the rake face with a certain distance away from the cutting edge. The highest chip temperature all appears on the side which interacts with the rake face. It can also be found from Figure 3 that the internal temperature of the workpiece does not change significantly, and the machined surface temperature is also remarkably lower than that of the chip temperature. This is caused
by the reason that the chips take away most of the heat generated by the plastic deformation of the cutting layer, and a relatively smaller amount of heat is transmitted into the workpiece.

3.2. Cutting temperature distribution under different cutting thickness

When the milling speed $v_c = 200$ m/min, and the feed per tooth is $0.1$ mm/z, $0.3$ mm/z and $0.5$ mm/z (namely, the corresponding equivalent uniform cutting thickness $h_e$ is $0.064$ mm, $0.191$ mm and $0.318$ mm, respectively), the cutting temperature distribution is displayed in Figure 4. It can be observed that the temperature of the tool-chip contact area and the machined surface temperature increase as the cutting thickness increases. In the meanwhile, the chip thickness also increases as the cutting thickness increases.
3.3. Cutting temperature distribution under different milling speed
When the feed per tooth is 0.3 mm/z (i.e., the corresponding equivalent uniform cutting thickness \( h_e \approx 0.191 \) mm), and the milling speed is 160 m/min, 200 m/min and 240 m/min, the cutting temperature distribution is presented in Figure 5. It can be found that the temperature of tool-chip contact area and the machined surface temperature increase with the increase of milling speed.

4. Conclusions
In this work, the finite element simulations of rail milling have been conducted in detail based on a modified Johnson-Cook constitutive model, and the following conclusions can be drawn:

(1) Based on the equivalent uniform cutting thickness, 3D rail peripheral milling process is converted into the 2D orthogonal cutting process. An appropriate 2D orthogonal cutting model of rail milling process is established with a modified Johnson-Cook constitutive model.

(2) The maximum temperature of the cutting tool appears somewhere on the rake face with a certain distance away from the cutting edge. The highest chip temperature all appears on the side which interacts with the rake face. The internal temperature of the workpiece does not change significantly, and the machined surface temperature is also remarkably lower than that of the chip temperature.

(3) With the increase of milling speed and cutting thickness, the temperature of tool-chip contact area and the machined surface temperature show an upward trend.

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References
[1] Daves, W., Kráčalík, M., Scheriau, S. (2019) Analysis of crack growth under rolling-sliding contact. Int. J. Fatigue, 121: 63-72.
[2] Liu, P.J., Quan, Y.M., Wan, J.J., et al. (2020) Experimental investigation on the wear and damage characteristics of machined wheel/rail materials under dry rolling-sliding condition. Metals, 10, 472.
[3] Steenbergen, M., Dollevoet, R. (2013) On the mechanism of squat formation on train rails-Part I: Origination. Int. J. Fatigue, 47: 361-372.
[4] Li, H.Z., Wang, J. (2013) A cutting forces model for milling Inconel 718 alloy based on a material constitutive law. Proc. Inst. Mech. Eng. Part C-J. Eng. Mech. Eng. Sci., 227(8): 1761-1775.
[5] Dandekar, C.R., Shin, Y.C. (2012) Modeling of machining of composite materials: a review. Int. J. Mach. Tools Manuf., 57: 102-121.
[6] Meng, X.X., Lin, Y.X. (2020) Chip morphology and cutting temperature of ADC12 aluminum alloy during high-speed milling. Rare Metals, 1-9.
[7] Liu, P.J., Quan, Y.M., Ding, G. (2019) Dynamic mechanical characteristics and constitutive modeling of rail steel over a wide range of temperatures and strain rates. Adv. Mater. Sci. Eng.,
2019, 15.

[8] Filice, L., Micari, F., Rizzuti, S., et al. (2007) A critical analysis on the friction modelling in orthogonal machining. Int. J. Mach. Tools Manuf., 47(3-4): 709-714.

[9] Sartkulvânic, P., Sahlan, H., Altan, T. (2007) A finite element analysis of burr formation in face milling of a cast aluminum alloy. Mach. Sci. Technol., 11(2): 157-181.

[10] Cockcroft, M.G., Latham, D.J. (1968) Ductility and the workability of metals. J. Inst. Metals, 96(1): 33-39.