High-speed Cold Roll Forming Roll Rolling Thermal Coupling Friction Simulation Analysis

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Abstract: In order to reveal the impact of the rolling thermal coupling friction on the cold roll-beating during high speed cold roll-beating forming process, involute spline as the research object, established a high-speed cold roll-beating finite element model, the changes of elasto-plastic deformation and thermo-mechanical coupling stress during involute spline cold roll-beating contact are studied; and the distribution of temperature, stress and strain field under a single stroke; the stress, strain and temperature curves of the key elements are extracted, and the influence of temperature on the thermal coupling stress and strain is analyzed. The results show: in the process of cold roll-beating, the gradient distribution of strain field, temperature field and stress field in the area of severe deformation is very large, while the temperature, stress and strain of other small deformation areas are low; high strain and high temperature are mainly distributed in the direct contact with the rolling wheel surface area; the temperature generated during cold roll-beating reduces stress and increases the effectiveness of metal flow.

1. Introduction
High-speed cold roll-beating forming technology is an advanced, green plastic forming technology, the use of the plasticity of metal materials, through the high-speed rotating wheel hit the workpiece hit and roll, the metal material flow, gradually make the blank to form the required features with complex shapes. During cold roll-beating forming, rolling of the rolling wheel causes plastic deformation of the work piece and causes violent friction between the rolling wheel and the work piece; high stress, strain and temperature are formed in the deformed area of the work piece, and results in multiple fields of the coupling effect; resulting in the workpiece material shock behavior, the physical behavior of the material mutation. Therefore, it is of great significance to study the formation mechanism of friction coupled with high-speed cold roll-beating and rolling heat.

Zhu Wenjuan summarizes the status quo and development trend of high-speed cold rolling technology research, through high-speed impact and static tests, obtained 40Cr J-C equation parameters, a high speed cold roll-beating involute spline thermal coupled finite element model was established, and the stress, temperature and strain distribution, the influence of rolling radius, constitutive equation and friction coefficient on cold roll-beating was studied. Yao Lei adopted the ABAQUS finite element simulation and the test combined with the way, the analysis of the gear blank material during the cold roll-beating process of the change of the strain, temperature and stress changes, established a cold roll-beating gear temperature analysis model, studied the effects of material, processing parameters and friction factor on the cold roll-beating process.
However, there are few researches on the thermal coupling of cold roll-beating spline, especially the cold roll-beating sliding thermal coupling friction analysis has not been reported publicly. Therefore, in this paper, finite element simulation analysis method is used to study the cold roll-beating sliding thermal coupling friction analysis during high-speed cold forming, by extracting the simulation results of the single-shot high-speed cold roll-beating finite element model, the variation and distribution of stress, strain, temperature and metal flow in the rolling process are obtained, discussed the mechanism of high-speed cold roll-beating forming and analyzed the influence of temperature on the cold roll-beating sliding thermal coupling friction.

2. High-speed cold roll-beating finite element model established

Fig.1 Geometric model of cold roll-beating.

2.1 Finite element geometric model
Involute spline shaft parameters: m=2.5, z=14, the pressure angle of 30°, the tooth top coefficient ha*=0.5, root high coefficient hf*=0.75. Since cold roll-beating spline forming is a problem with plane symmetry, it is only necessary to consider half of the machining system in finite element analysis. Take a length of the workpiece, the establishment of the finite element model of the geometric model shown in Figure 1. The semi-circle radius of the workpiece finite element model is 17.5mm and the length is 20mm. Rolling wheel radius of 19mm, width of 8mm, fillet radius of 0.5mm.

2.2 Dividing the mesh
The mesh length of the cell mesh for the partial contact is 0.12mm, the length of the bisector of the other cell grids is 2mm, and the grid type is the thermocouple hexahedral cell C3D8RT. Rolling material for the Cr12MoV, in the rolling process occurs only minimal elastic deformation, it will set the rolling wheel to analyze rigid body, do not need to divide the grid.

2.3 Material model
Through the Hopkinson test platform on 20 steel dynamic compression test, the workpiece material obtained at different temperature and strain rate stress strain data to calculate the material JC model parameters [9,10] as shown in Table 1, 20 steel physical parameters The density of the workpiece is 7.85 × 103kg / m3, the elastic modulus is 213Gpa, the Poisson's ratio is 0.282, the specific heat capacity is 470J /(kg·k) and the thermal conductivity is 44W / (m·K).

| A(MPa) | B(MPa) | C  | m       | n       | T(K) | δ0(s⁻¹) | Tm(K) |
|-------|-------|----|---------|---------|------|---------|-------|
| 213   | 53    | 0.051 | 0.76   | 0.345   | 293  | 0.004   | 1623  |

2.4 Boundary conditions
Rigid body reference point is the rotational axis of the rolling wheel, and the rolling wheel rotational speed (2000 r / min) is loaded on the rigid reference point of the rolling wheel; the feed amount of movement along the positive x-axis is loaded on all nodes of the workpiece 1mm / s). The plane of symmetry of workpieces is subjected to a plane-symmetric constraint and the coefficient of friction is set to 0.2. The strain heat generation coefficient of the workpiece is 0.9, and the initial temperature of the workpiece material is defined as 20 ° C.
3. High Speed Cold Roll-beating Rolling Thermal Coupling Friction Simulation Results and Analysis

3.1 Equivalent strain distribution at different times
In the high-speed cold roll-beating process, figure 4 shows the workpiece at different times the equivalent stress distribution. Figure 4 (a) shows the equivalent stress distribution of the workpiece when the rolling wheel is in contact with the workpiece. The equivalent stress distribution of the workpiece during the impact of the rolling wheel on the workpiece is shown in figure 4 (b) and 4 (c) shows; when the rolling wheel breaks away from the workpiece, the equivalent strain distribution is shown in figure 2 (d).

![Fig.2 Equivalent strain distribution at various times](image)

As can be seen from figure 2, during the cold roll-beating process, the equivalent strain and its distribution range of the rolling wheel and the workpiece gradually expand, the nonuniformity of the workpiece deformation aggravates. The larger equivalent strain is the workpiece and the rolling wheel Contact both sides and bottom surface area. The curves of the equivalent strain changes with time of each key unit are shown in figure 3.

The curve of the equivalent strain of the unit shown figure 3 is similar. When the rolling wheel contacts with the workpiece, the equivalent strain of the unit is zero. As the contact between the rolling wheel and the workpiece, the unit equivalent plastic strain rapidly rises High, rolling wheel and the workpiece detachment, the unit equivalent strain maintained at a stable value. This is due to the contact between the rolling wheel and the workpiece, the high-speed rotation of the rolling wheel into the workpiece and each unit contact plastic deformation of the workpiece, with the high-speed rotation of the rolling wheel, roll the wheel from the unit, the unit The equivalent plastic strain is also maintained at a relatively stable value. The equivalent plastic strain of the cell 1478 and the cell 1479 is the largest, and these two cells are at the involute root of the formation, indicating the most difficult metal flow at the tooth root. Unit 1483 is at the top of the tooth, the metal flow is the easiest, and the equivalent plastic strain is the smallest. Unit 1477 located at the bottom of the tooth, the strain rate of rise is small, but the change time longer, the process is relatively stable.

3.2 Equivalent stress distribution at different moments
In the high-speed cold roll forming process, figure 4 shows the workpiece at different times the equivalent stress distribution. Figure 4 (a) shows the equivalent stress distribution of the workpiece when the rolling wheel is in contact with the workpiece. The equivalent stress distribution of the workpiece during the impact of the rolling wheel on the workpiece is shown in figure 4 (b) and 4 (c)
shows; when the rolling wheel breaks away from the workpiece, the equivalent strain distribution is shown in figure 4(d).

![Fig.4 Equivalent stress distribution at various times](image)

(a) t=0.45ms          (b) t=0.72ms        (c) t=1.08ms       (d) t=1.275ms

It can be seen from figure 4 that the maximum stress occurs partly on the interaction between the rolling wheel and the workpiece. When the rolling wheel just touches the workpiece, the equivalent stress in the deformation area of the workpiece is the largest, but the distribution range of equivalent stress is small. With the progress of cold strike, the equivalent stress decreases gradually, and the range of equivalent stress distribution gradually increases, and the non-uniformity of equivalent stress distribution aggravates. The selection of units 1478, 1480 and 1483, respectively, represents the change in the equivalent strain at the tooth root, pitch circle and tooth tip as shown in figure 5.

![Fig.5 Stress curve of key elements](image)

It can be seen from figure 5 that the equivalent stress of the unit 1478 at the tooth root is the highest because the equivalent strain here is the largest and the metal flow is difficult. The unit 1483 at the tip circle is the smallest, mainly due to the metal at the tooth tip flow is the easiest and the equivalent plastic strain is the least. With the cold forming process, the equivalent stress of the deformed part of the workpiece gradually decreases after reaching the maximum value. This is mainly due to high-speed cold roll-beating start hitting the workpiece, due to the role of stress waves, resulting in a sharp increase in workpiece stress; in the rolling wheel to leave the workpiece, due to the workpiece to stop deformation, the equivalent stress of the three units have varying degrees of Decrease.

### 3.3 Node temperature distribution at different times

In the high-speed cold roll-beating process, Figure 6 shows the temperature distribution of the workpiece at different times. Figure 6 (a) shows the temperature distribution of the workpiece when the rolling wheel touches the workpiece. The temperature distribution of the workpiece during the impact of the rolling wheel on the workpiece is shown in Figure 6 (b) and 6 (c); When the roller is separated from the workpiece, the temperature distribution is as shown in Figure 6 (d).

![Fig.6 Node temperature distribution at various times](image)

(a) t=0.45ms          (b) t=0.72ms        (c) t=1.08ms       (d) t=1.275ms

As can be seen from Figure 6, a region with a higher temperature occurs in a portion where the workpiece comes in contact with the rolling wheel, and the temperature distribution in the rolling direction is not uniform. And the node temperature distribution is similar to the equivalent plastic strain of the workpiece. Extraction node temperature and time curve tracking analysis, the node temperature changes with time for the curve shown in Figure 7.
As can be seen from Figure 7, with the cold roll-beating process, the temperature of the key nodes in all parts of the workpiece suddenly increases and then decreases, but the rising and falling slopes of the key points in each part are different. This is mainly due to the rolling wheel into the workpiece, rolling wheel and the workpiece contact with the friction and plastic deformation of the workpiece into heat, the workpiece temperature increases; with the rolling wheel and the workpiece out of contact with the workpiece no longer Friction and plastic deformation temperature rise, and due to heat exchange between the workpiece and the environment and the workpiece temperature rise to other parts of the workpiece heat transfer, the workpiece temperature gradually decreased.

4. Analysis of Thermal Effect on Rolling and Friction of High Speed Cold Roll-beating

4.1 Analysis of the influence of temperature, stress and strain

In order to study the spline profile on the various units with or without thermal effects of strain changes, as shown in Figure 8. As can be seen from Figure 8, there is almost the same tendency of the curves of the various cells with and without temperature action. The strains of units 1478, 1480 and 1483 that do not consider the thermo-softening effect are both lower than those that take into account the thermo-softening effect. This is because during the cold roll-beating process, the temperature of the deformation zone increases due to the heat generated by the plastic strain and the friction, which softens the material and deforms more easily.

Using the above method to study the effects of temperature, the variation of unit stress with time in two cases is obtained, as shown in Figure 9. In both cases, the stress of each unit changes in the same direction. After contact between the rolling wheel and the work piece, the root softening unit 1478 and the dividing unit 1480 do not consider the thermal softening effect larger than the softening effect, Unit 1483 does not consider the thermal softening effect less than the softening effect. The stress values of the three elements considering the thermo-softening effect are relatively close during the striking process, while the stress values of the individual elements without considering the thermo-softening effect are relatively dispersed. This is because the temperature rise caused by plastic deformation and friction in the hitting process increases the fluidity of the workpiece material, so that the stress at each point of the forming surface is relatively close, and avoiding some points in the process of stress is too high.

4.2 Analysis of the Influence of Temperature and Metal Flow

In order to study the metal flow of each node on the spline tooth profile, the displacement of the node 137 at the addendum, the node 139 at the indexing circle and the node 142 at the tooth root with or without thermal softening changes with time. As shown in Figure 10. The node at the addendum 137 has the largest node displacement and the root node 142 has the smallest displacement because of the
During thermal softening, and the node displacement at the top of node 137 is the largest, the thermal softening is the most obvious, and the softening of the root node 142 is the weakest. The law of least resistance to metal flow and the softening effect determine.

5. Conclusions

Through the simulation, we get the following conclusions: cold rolled spline metal fluidity from strong to difficult are: addendum > dividing circle > dedendum. During the cold roll-beating process, the high strain and high temperature are mainly distributed in the surface area which is in direct contact with the rolling wheel, and the stress, strain and temperature in the deformation area change sharply; workpiece stress distribution, equivalent plastic strain distribution and temperature distribution are not uniform. The equivalent strain and node displacement of involute tooth surface considering thermal softening effect are larger, the stress values of each unit surface on the tooth profile surface are relatively average when thermal softening effect is considered, and when considering the contact during thermal softening Force that do not consider the role of heat softening small.

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