Three-dimensional finite element analysis for flying shearing of X100 hot-rolled steel plate

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Abstract

Increasing demands for transporting oil and natural gas promote the developing and production of high-grade pipeline steel. The hot rolling is a vital process to produce the steel plate of pipe fabrication. In a hot rolling line, a flying shear is used to shear the leading and trailing edges of a rough rolled plate. In the present research, three-dimensional FE model of flying shear was built on ABAQUS/Explicit, considering the motions of blades. The feeding rollers and shear blades are considered as rigid material, and the steel plate adopts elastic-plastic material model. Ductile damage criterion for X100 steel was built to simulate the material damage and fracture during the shear processing. By the simulation, the plastic deformation, the damage initiation and evolution, the fracture of steel plate can be obtained, which are coincided to production practise. The stroke-force curves of blades were generated from the FE simulation. The shearing force varying with the blade stroke was analyzed. FE simulation shows that the calculated force from FE model is much lower than that from empirical equation.

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1. Introduction

API (American Petroleum Institute) X100 steels are considered to be the important construction of the next generation of pipelines which are produced through the hot rolling line (Ghajar et al., 2013; Nonn and Kalwa, 2012; Rosado et al., 2013). In a hot rolling line, a flying shear follows the rough rolling mill and shears the leading and tailing edges of a rolled plate. The sheared plate is fed into a finishing rolling stand. The flying shear is an important equipment of rolling line and its working performance directly influences production efficiency and fracture surfaces quality of rolled plates.

During the flying shearing, the two blades have to keep pace with the feeding plates in horizontal direction. Thus, the steel plate is cut along the vertical direction, avoiding the “drag” or “stack” of steels in the fracture region, especially for thick steel plates. With respect to the kinematics of the flying shear, there are many deep researches and are maturely applied in industry. However, the steel plate undergoing the complicated deformation, damage and fracture during the flying shearing has not been thoroughly studied. There are still some challenges in calculation of the material deformation and shearing load evolutions of the blades. Flying shearing differs from the operations of blanking and punching, because the materials are cut in two directions simultaneously due to the complex motions of the blades. For the simulation of the flying shearing, a three-dimensional analysis of the process has to be conducted. However, there is limited research on 3-D finite element simulation of fly shearing. Some researchers conducted some investigations on slitting simulation. Wisselink (2000) used ALE (Arbitrary Lagrangian and Eulerian) finite element code Dieka to simulate slitting and guillotining, where shearing occurred at room temperature and stationary. Aggarwal et al (2005) modelled the slitting process of magnetic tape. Relative to the feeding direction, the plate or sheet is cut longitudinal in the slitting, but is cut transversely in the flying shearing. The more complex motions of the blades during the flying shearing than that of slitting and guillotining should be considered.

In present research, 3-D finite element simulations for the flying shearing of X100 pipeline steel plates are conducted. The flying shear under investigation is crank type, and shearing blades move with the crank of shear machine, which will be embodied in finite element models. Generally, the ductile damage only happens after materials undergo large plastic deformation and the initial damage position is random, so a 3-D FE model is necessary for simulating flying shear processing. To this end, isothermal compression tests of X100 over a large range of strain rates were carried out to obtain stress and strain data for defining the material model in the simulations. In addition, damage criterion was determined by a method combining experiments and simulations. The flying shear model was developed on ABAQUS/Explicit and the results accurately described the flying shear process.

2. Finite element model

The FE model of flying shear contains the top and bottom blades, the rolled steel plate and three feeding rollers, and their initial relative positions are shown in Fig. 1. During the working, three feeding rollers rotate anti-clockwise and drive the plate forward (left) by friction between rollers and plate. Two blades move along elliptical orbit (determined by cranks of the shear machine) and have the same horizontal velocities with the feeding plate, which is necessary conditions of the flying shearing process.
Fig. 2 shows the geometry models of two blades. The herringbone cutting edge of top blade contacts the steel plate from two sides to middle gradually when the top blade moves downward. Compared to the flat shear blade, the herringbone blade undergoes lower shearing force due to the decreasing transient contact areas. Corresponding to this, the top and bottom blades are both concaved in front-back direction. Considering the geometry and loading conditions of the shear blade and steel plate, symmetrical FE models were established with a half of structures. The top and bottom blades and three feeding rollers were treated as discrete-rigid using element R3D4 of ABAQUS. The plate material, X100 steel, applied elastic-plastic data derived from experiment tests. The plate was meshed by eight-node hexahedral elements C3D8R. The dimension of plate is 40mm in thickness, 1950mm in width and 4210 mm in length. The shearing clearance between two blades is 0.2mm. Fig 3 is the diagram of 3-D FE model of flying shear process.

In ABAQUS, the definition of the material failure consists of three parts: undamaged material response, a damage initiation criterion and a damage evolution law. Influences of the temperature and the speed on the flow stress of material are significant for metal hot working simulation. In simulation of the flying shearing, undamaged material data including the flow stress varying with strain, strain rate and temperature were determined by isothermal uniaxial compression tests of X100 pipeline steel. The flying shearing is finished in very short time, so the heat generation and dissipation of plate material were omitted. The deformation and shearing temperature is 900°C, and the flow stress data at 900°C were adopted in FE model. Fig.4 shows the flow stress varying with strain rate at 900°C. Young modulus $E$ and Poisson ratio $\nu$ of X100 pipeline steel were taken to be $E=28000$ MPa and $\nu=0.3$.

Ghosh et al (Ghosh et al., 2005) considered the shear failure as the most suitable model to simulate the shear-slitting processes. In present simulation, the shear damage model was adopted. The value of the equivalent plastic strain $\varepsilon_{pl}^p$ at the onset of damage was material parameter for the specification of the damage initiation. The damage evolution law was specified in terms of equivalent plastic displacement $\pi^p$. These two parameters were commonly determined by hybrid experimental-numerical methods(Li et al., 2011; Lou and Huh, 2013). In present study, four types of specimens were utilized to obtain their value in tensile and shear tests at 900°C using the method combining experiments and simulations. $\varepsilon_{pl}^p$ is defined as 0.5 and $\pi^p$ is 3.0.

The horizontal feeding velocity of the plate was 1750 mm/s, and was defined by the equivalent rotation speed of the feeding roller. Vertical and horizontal velocities of blades obey the kinematic laws. Data calculated by kinematics design were transferred into definition of boundary conditions of blades. The elliptical locus of two
blades shown in Fig. 5 (a) were obtained from motion analysis of key structures during flying shear process. Only shear region is focused on in the FE simulation, vertical velocities of blades in this phase with the time are plotted in Fig 5 (b).

![Fig. 4. Flow stresses of X100 steel varying with strain rate at 900 °C.](image)

![Fig. 5. Motion locus and velocity of two blades: (a) elliptical locus; (b) vertical velocity during shear region.](image)

3. Simulation results and discussion

Finite element simulations of the flying shearing according to the built model in last section were conducted on ABAQUS/Explicit. Fig. 6 shows the simulated flying shearing process of X100 pipeline steel, where the main four stages from plastic deformation, damage to fracture separation are included. During the shearing of the steel plate, the deformed materials initiate ductile damage when the equivalent plastic strains reaches 0.5. After that, the rate of degradation of the material stiffness keeps growing and when the material stiffness is fully degraded, the elements are removed from calculation whereby failures appear. As the overlaps between two blades become bigger, the failures propagate from sides to the centre until the total fracture are arrived as shown in Fig. 6(d).
In simulation results, the variable SHRCRT represents the effects of accumulated plastic strains $\sum_{i}^{} \varepsilon_{pl}$ and is defined as the ratio of the sum of plastic strain increment of each step to the present value of $\sum_{i}^{} \varepsilon_{pl}$. As a consequence, the maximum value of SHRCRT becomes 1.0 as the equivalent plastic strain of some materials are bigger than 0.5. The plastic strain and SHRCRT are shown in Fig. 7(a) and (b), and their maximum value exceed or equal their critical values. It indicates that the simulated results coincide well with the preset value. At this stage, the damage evolution comes into effect and its damage variable (denoted by SDEG) is smaller than 1.0 (Fig. 7c). That is to say, the materials need more plastic deformation to become failure when the value of SDEG is 1.

Fig. 8 plots calculated shear forces of top and bottom blades during flying shear process. At the beginning of shearing, the two blades are on idle stroke because the cutting edges don't contact the plate. The top and bottom blades move downward and upward with the same speed, respectively. After an idle stroke 4 mm, the bottom blade contacts the bottom surface of plate instantaneously. Consequently, the bottom blade undergoes a large impact force with a drastic fluctuation and a peak value about 1800 kN. With its upward movement, the bottom blade picks up the steel plate gradually from the rollers, therefore weight of steel plate increases the force of the bottom blade. When the blades move more than 10mm, the top blade penetrates into the plate and the shear force increases with growing shear areas. The shear force of top blade reaches its peak value at the displacement of 28mm and keeps steady and then slightly declines. Shear areas at both sides of the plate, the plate mass and the accelerations of blades affect the force of bottom blade and the latter dominates the force even when the shear area is getting smaller. The maximum force of the bottom blade occurs later and is larger than that of the top blade. Without
considering material damage, the theoretical peak shear force on basis of oblique-edge shear theory (Shamoto and Altuntas, 1999) is calculated by

\[ F = Kt^2 \frac{r}{\sin \phi} \]

where \( K \) is safety factor, 1.2; \( t \) is plate thickness, 40 mm; \( r \) is shear strength, 200 MPa; \( \phi \) is blade angle, 4°. The shear load is calculated as 5491 kN by the empirical equation (Eq.1), which is much greater than the peak value of the calculated force by FE simulation. That is because material damage, rate-dependence flow stresses and horizontal velocities of blades and plate are considered to get the lower shear force, which are not taken into account in empirical equation.

![Shear forces of top and bottom blades during flying shear process.](image)

Fig. 8. Shear forces of top and bottom blades during flying shear process.

4. Conclusions

The three-dimensional FE model of flying shear process of hot-rolled steel X100 was developed on ABAQUS/Explicit. Shear damage criteria was used to simulate the damage initiation and evolution of materials during the shearing. The following conclusions can be drawn:

1. Features of flying shear process were analysed and the 'herringbone' top blade and 'convex-concave' fitting surfaces of two blades were beneficial to induce shear load and scrap materials.
2. The shear ductile fracture criterion is calibrated by the equivalent plastic strain measured by the hybrid experimental-numerical method.
3. The fracture evolution locus of steel plate and parameters representing damage initiation and evolution were studied. The simulation results were in good agreement with the preset damage criterion.
4. Shear forces of top and bottom blades were different and their peak values were both smaller than the theoretical value calculated by oblique edge shearing theory, which indicated the advantages of flying shear and special shapes of two blades adopted here.

References

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