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Analysis of laminated crack defect in the upsetting process of heavy disk-shaped forgings

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ABSTRACT

Using nonlinear finite element method, a thermo-mechanical coupled simulation model for the formation mechanism of the laminated crack defect has been established in the upsetting of heavy disk-shaped forgings. Through numerical simulation, the distributions of stress, equivalent strain and strain rate were analysed. Meanwhile the distribution diagram of stress state evolution was obtained, and the uncoordinated deformation, under tri-lateral compression, is determined as the main reason leading to laminated crack defect. To reveal the characteristics of the uncoordinated deformation, the variations of each variable and its gradient in numerical simulation were presented, and a combined prediction model of laminated crack defect were proposed based on degree of deformation and gradient of deformation speed. Subsequently, the morphology and distribution of laminated crack were obtained in the centre of forging using the prediction model. Comparison of calculation results and experimental data indicates that both of them match well. In addition, the effect of friction coefficient on the deformation is also presented. The results show that the decreasing of friction coefficient is an effective measure to restrain the laminated crack defect.

1. Introduction

Heavy disk-shaped forgings are commonly used for key parts of equipment in the nuclear, electronics, and heating fields, such as tube plate and impeller in turbine boiler, top cover of pressure vessel for nuclear reactor, tube plate of heat exchanger, and bottom head of chemical containers. The forming of the disk-shaped forgings is carried out by forging, and mainly upsetting. In the upsetting process, the defects of the cast dendritic microstructure and shrinkage porosity will be fixed by larger forging ratio in order to improve the quality of forgings. According to the theory of plasticity, if friction is ignored, the upsetting between flats can be simplified to be the single compression. However, the existence of friction leads to complex changes of the stress–strain state in the forgings, many problems cannot be solved, and even cannot be qualitatively analysed [1]. Therefore, there were some misunderstandings on the upsetting of cylinder between flats in a long period of time, namely state of tri-lateral compressive stresses is always produced in the centre of deformation body, regardless the ratio of height to diameter (transient state) of the forging [2,3]. In response to this problem, Prof. Liu [3] proposed two new theories, namely the tensile stress theory of rigid-plastic mechanics [4–6] and the shear stress theory of hydrostatic stress mechanics [7,8], which presented the evolution law of

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complex stress state in the forgings, and the qualitative physical simulation experiments were also carried out [4]. Subsequently, the theories were verified by aid of the Generalised Slip-line Method [9] and Mechanical Slab Method [10].

Inner laminated crack during upsetting is a serious forging defect of disk-shaped forgings, which reduces the qualified rate of ultrasonic inspection of forgings, and significantly affects the mechanical properties of materials and safety performance. Recent plastic mechanics theory cannot explain horizontal-type laminated crack defects. Many scholars presented different views on its formation mechanism, which include hydrogen flaking, inclusions and unclosed porosity under axial compression [11–13]. RST effect (Rigid Slid Tearing Effect) is also proposed [14,15], that because the deformation energy needs to be released after two rigid areas contact, if forced deformation under compressive stress continues, it will lead to laminated rigid slip deformation, and tearing failure occurs when reaching the material allowed strength of shear strain. Shear stress theory of hydrostatic stress mechanics proposed by Liu [7,8], exposes mechanical behavior and deformation mechanism of the centre of the sample during upsetting when the ratio of height to diameter of forgings is less than 1. It is believed that the stress state in the stagnant deformation zone at the end of forging is hydrostatic pressure, where the shear stress can exceed critical shearing strength of material and laminated shear crack parallel to the section appears where the shear deformation is very significant, namely reaching the critical condition. However, most investigations on heavy forging defects in the upsetting process focus on both the surface crack [16–18] and closing bonding of inner void [19–24] of the forgings in recent years. Based on the above, there is not a uniform interpretation to the inner laminated crack of large forgings and its criterion model yet. So it is of great significance on the detailed theoretical analysis of its evolution law of deformation mechanics.

With the increasing maturity of finite element analysis (FEA) technology, it has become the consensus that finite element method (FEM) is selected as a powerful tool to solve many practical problems. In the past years, commercial FEA software MARC was used to simulate the closing process of the inner crack in cylindrical body during hot upsetting, and analyze the stress and strain of the crack during deformation and various factors that affect closing and bonding of the inner crack [25]. Banaszek [19,20] studied the upsetting process of a cylinder with a void by the commercial FEA software Forge. And through simulation, they investigated the influence of forging processing on the internal void closure of the forgings and gained the reasonable forging conditions of defect-free. Based on DEFORM software, the thermal–mechanical coupled model of upsetting process was established separately by Zhang [17] and Huang [26], to investigate the effect of upsetting parameters on centre compaction and void changing. According to simulated results, improving measures were proposed. A thermo-mechanical coupled model of heavy disk-shaped forgings in the upsetting process was established using rigid-plastic finite element method in this study. Based on the model, the evolution of stress–strain state and the deformation gradient distribution in the upsetting process was presented for the ratio of height to diameter greater than 2 ($H/D > 2$), and then the formation mechanism of laminated crack defect was investigated. At last, a criteria model for laminated crack of the disk-shaped forgings was proposed and verified.

2. Finite element model

2.1. Basic theories of the rigid-viscoplastic thermal–mechanical finite element model

The analysis of the upsetting process makes use of the rigid-plastic FEM based on the flow formulation of the penalised form of the incompressibility. According to the variational principle, the basic equation for the finite-element formulation is expressed as:

$$\int_V \overline{\sigma}\delta\overline{\varepsilon}\ dV + K\int_V \varepsilon_v \delta\varepsilon_{ij}\ dV - \int_{S_F} F_i \delta u_i\ dS = 0 \tag{1}$$

where $\overline{\sigma}$ is the equivalent stress, $\overline{\varepsilon}$ is the equivalent strain rate, F_i represents surface tractions, u_i is the velocity field, K is a penalty constant that is a very large positive constant. $\varepsilon_v = \varepsilon_{ij}$, is the volumetric stain rate.

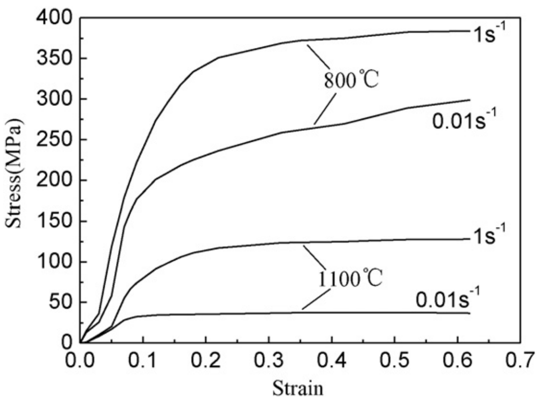

Fig. 1. True stress–strain curve.