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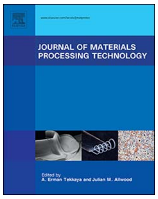

Research Paper

Micro-mechanism of central damage formation during cross wedge rolling

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ABSTRACT

Central damage is a serious defect in the solid products of cross wedge rolling. A combined experimental and modelling approach was used to study the micro-mechanism of central damage. The evolution process of the micro-voids initiation, growth and coalescence during cross wedge rolling of steel was observed, and the micro-damage morphology was linked to the stress-strain state to reveal the mechanism of central damage. The influences of process parameters on the central damage were investigated on the basis of analyzing the characteristics of stress and strain in the center of the workpiece. It is found that the micro-voids in the center of the workpiece initiate around non-metallic inclusions and develop into macroscopic damage in the directions of shear stress and tensile stress by growth and coalescence; the shear stress and tensile stress cause significant alternating shear and tensile deformation with the rotation of the workpiece, leading to the central damage. The larger the shear deformation and tensile deformation coefficient, the more the cyclic numbers, the greater the degree of damage; among the process parameters of cross wedge rolling, the forming angle has the greatest influence on the central damage.

1. Introduction

Cross wedge rolling (CWR) is a kind of metal plastic forming process of high efficiency, materials saving and good production environment. It has been widely used in the production of shaft parts on the automobiles, gearboxes and so on. Central cavity is a serious defect in the solid products of cross wedge rolling, which weakens the mechanical strength of the workpiece and eventually results in product failure. Avoiding the internal defects in the products of wedge cross rolling has been a major concern in the development of process. Smirnov (1947) studied the cause of internal defects and recognized that shear stress and tensile stress led to the formation of central damage. Teterin and Liuzin (1960) found there was an intense plastic deformation zone in the center of the billets by conducting tests on composite steel billets. Danno and Awano (1976) observed that the size of central cavity increased with the number of revolutions in the rolling experiments and supported the view that the repeated tensile stress and shear stress resulted in the growth of central cavity. Hayama (1979) developed an approximate formula by a slip-line method of plane strain to calculate the tensile stress in the center of stepped shafts and obtained the optimum working conditions to avoid the central damage. Fu and Dean (1993) reviewed the developments and applications of cross wedge rolling, including an overall summary of the forming cause of central defects. Dong et al. (2000) established a three-dimensional finite element (FE) model of cross wedge rolling, including the knifing and guiding stages, and claimed that internal damage would occur when the first principal stress in the center of the workpiece exceeded yield stress. Li et al. (2002) analyzed the influence of three primary parameters from the experimental results of cross wedge rolling 1100 H16 alloy aluminium, and defined a non-dimensional deformation coefficient to predict the likelihood of void formation. Li and Lovell (2004) drew a conclusion that the effective plastic strain was the best criterion for predicting the internal damage on the basis of numerical simulation results. Pater et al. (2005) confirmed the highest possibility of cracks was in the central region of workpiece due to positive mean stress by the result of numerical analysis of cross wedge rolling ball pins. Silva et al. (2011) found that the high sulfur content associated with a high working temperature determined the formation of large central cavities in the rolled parts. Kache et al. (2012) applied cross wedge rolling at warm temperatures and found that the process parameters were the main factors of internal cavity rather than the value of temperature. Zhou et al. (2014) established a finite element model for multi-wedge cross wedge rolling to analyze the generation mechanisms of internal defects and indicated that micro-cracks were produced by shear stress cycle, and then developed to cracks due to the high first principle tensile stress caused by metal backflow. Huang et al. (2014) investigated the

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influence of wedge-tip fillet on the internal defects and found the increasing transverse stress and shear stress would lead to higher possibility of internal defects with the increase of the wedge-tip fillet. To sum up, the formation of central damage in the CWR process is attributed to several possible causes and there are no consistent viewpoints due to limitations of the research approaches and conditions, and more researches are required to provide reasonable evidences to reveal the forming mechanism of the central damage.

It is important to obtain the detailed characteristics of damage zones in order to understand the forming mechanism. Maire et al. (2005) used X-ray absorption tomography to measure damage in heterogeneous model materials consisted of an aluminium matrix and spherical ceramic particles acting as nucleation sites. Farrugia (2006) developed a micro-FEM analyses model to predict the void volume fraction. The micro-FEM model can reveal the influence of inclusion, matrix, matrix/inclusion interface strength on damage formation. It was observed that the stress and strain were dependent on inclusion spacing and clustering. Kaye et al. (2013) found that during hot deformation the increase of spacing and size of inclusions led to necking, and then the localized damage grew further until coalescence occurred. A constitutive equation including clustering inclusions was proposed to capture the effect of stress localization between inclusions on damage growth. Daly et al. (2017) used a multi-scale correlative approach to investigate the nature of ductile fracture in metals, examining the ductile fracture of specimens by using X-ray computed tomography analyses and Scanning Electron Microscopy (SEM). The detailed characterization of microstructure and the information about the size, volume fractions and spatial distributions of voids were obtained, and it was found that the vast majority of large voids nucleated at MnS inclusions. From the above works, it is noted that the inclusions in metals are generally the main sources of voids and damage.

The formation and development of damage depends on the state of stress in material. Using a combined experimental and modelling approach, Foster et al. (2011) studied the modes of damage evolution in an experiment of bulk forming, and they found that microstructure is accurately linked to the corresponding stress state. The stress state is often measured in terms of stress triaxiality and Lode parameter. Zhang et al. (2001) analyzed the influence of Lode parameter values on the directional expansion of a void by three-dimentional numerical method and found that the influence of the Lode parameter was much stronger on void shape than on void volume fraction. Kiran and Khandelwal (2014) found at low triaxiality the Lode parameter had a significant effect on the microvoid elongation and dilation. Dunand and Mohr (2014) analyzed the effect of Lode parameter on plastic flow localization after proportional loading at low stress triaxiality and found that the overall shearing of the void was dominant and the void volume fraction remained approximately constant throughout loading at the intermediate stress triaxiality, and the void volume fraction increased at the high stress triaxiality. Brunig et al. (2015) confirmed that high positive stress triaxialities caused nucleation, growth and coalescence of micro-voids and nearly zero or negative stress triaxialities corresponded to isochoric formation of micro-shear-cracks. The tendency that tension loading leads to growth of voids whereas shear loading leads to formation of micro-shear-cracks was demonstrated by the SEM images. Due to the complexity of damage mechanism, it is impossible to capture all features of ductile crack formation in the different stress states with a single damage criterion (Bao and Wierzbicki, 2004). Although a number of ductile damage criteria are proposed based on experimental observations and numerical simulation, very few are actually applied and validated on complex industrial applications. Cao et al. (2015) carried out a comparative study of different ductile damage approaches for fracture prediction in cold forming processes and found that no model discussed can describe satisfactorily damage mechanisms at both high and low stress triaxialities. Benzerga et al. (2012) proposed the strain to fracture was not only a function of the current stress state, but also of the plastic loading history. In summary, damage models must account for different stress state and history in order to obtain correct results for complex loading applications. Novella et al. (2015) took into account the temperature and strain rate, and proposed a fracture criterion based on the stress triaxiality to model the damage evolution during a cross wedge rolling process of AA6082-T6bar by analyzing the fracture surface in tensile tests using SEM. Although the damage models that account for the tensile stress or stress triaxiality generally predict the correct location of damage, cross wedge rolling significantly differs from the simple tensile tests, because it's a complex 3D deformation process combined with the tensile and shear effects. Correct prediction of CWR central damage must depend on the state and history of stress and strain which is the most dominant factor to the ductile damage.

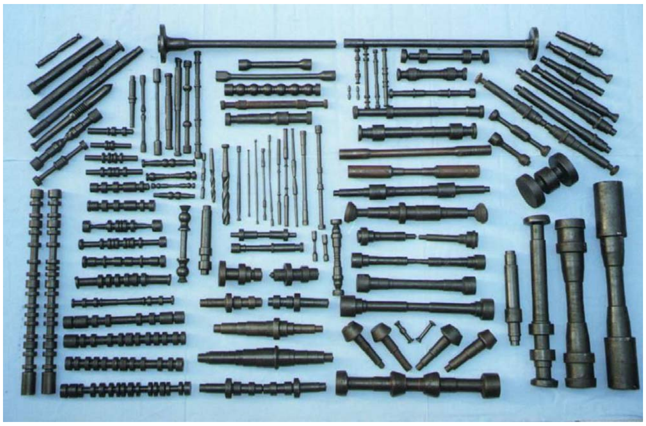

Fig. 1. Examples of cross wedge rolling products.

Hu et al. (2012) develop cross wedge rolling and this technology has been widely used in the industrial production for more than five hundreds types of products, and examples are shown in Fig. 1. Steel is the main engineering material, so the investigation on the damage mechanism of cross wedge rolling of steel is important to engineering application. The formation of macro-damage goes through the process of micro-voids initiation, growth and coalescence, and then the microscale approach is needed to reveal the nature and mechanism of central damage. In this study, we use SEM and energy dispersive spectroscopy (EDS) to analyze the microstructure, morphology and chemical composition, and use finite element simulation to predict stress and strain evolution during processing. Through the combined study, the mechanism of central damage of CWR steel workpiece has been revealed.

2. Rolling experiments

The flattened diagram of the cross wedge rolling tool and the formed workpiece are shown in Fig. 2. The CWR tool consists of the knifing zone, stretching zone and sizing zone. As indicated in Fig. 2, the process parameters of cross wedge rolling include the forming angle α, stretching angle β and area reduction ψ. The area reduction is determined by the relationship:

$$\psi = ((d_0{}^2 - d_1^2)/d_0{}^2)*100\% \quad (1)$$

where d_0 is the original diameter of the workpiece, d_1 is the formed diameter.

In order to investigate thoroughly the forming mechanism of central defects in cross wedge rolling process, it is necessary to obtain the different degrees of damage. Therefore, a wide range of parameters were chosen and central damages were generated under different rolling conditions: forming angles from 15° to 25°, stretching angles from 5° to 10° and area reduction from 15% to 75% as shown in Table 1.

The rolling experiments were carried out on the H630 two-roll cross wedge rolling machine at the University of Science and Technology Beijing as shown in Fig. 3(a), and the rolling machine has high rigidity