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Plastic evolution behavior of H340LAD_Z steel by an optical method

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ABSTRACT

An optical method based on digital image correlation (DIC) technology was proposed to measure the plastic evolution of the high-strength low alloy steel H340LAD_Z. The basic principle of DIC technology is introduced, and then, the use of a 3D deformation measurement system and electronic universal testing machine to dynamically measure plastic evolution during the tensile yield stage is described. Through the full-field full-process measurement of plastic deformation during the yield stage in the 0°, 45° and 90° loading directions, the plastic evolution law was revealed. The results demonstrate that the proposed 3D DIC method can accurately reveal the starting and ending times for plastic evolution. The specimens in the three directions exhibit different plastic evolution behaviors, although they have similar yield strengths and yield times. The specimens in the 45° and 90° loading directions began to enter plastic deformation from bottom to top and the plastic area was maintained in a constant deformed state, while the evolution behavior in the 0° direction transited from both sides to the middle and plastic deformation was uneven. It is important to study plastic evolution of a metal sheet to determine the material properties and to provide an accurate basis for finite element modeling.

1. Introduction

The high-strength low alloy steel H340LAD_Z is widely used in heavy vehicles, ships, and rockets because of its many excellent mechanical properties such as good plastic forming performance, small deformation resistance, and superior corrosion resistance [1–3]. To make full use of the excellent forming performance in industrial production, we must accurately determine the mechanical properties of the material. The yield stage is the transition stage between the elastic stage and hardening stage, and the plastic evolution behavior occurs in this stage, which is very important to research on the basic properties of metal material. In addition, the anisotropy of high-strength low alloy steel produced by a loading process has a great impact on the macro mechanical properties such as the strength, hardness and plasticity. Therefore, it is significant to study the plastic evolution law of anisotropic material to reveal the plastic forming mechanism. This can provide reliable data in the design and manufacturing of products and also has theoretical and practical significance in establishing the material constitutive model and improving the accuracy of the finite element simulation.

Currently, the traditional method to study the flow behavior of metal material is the use of the uniaxial tensile test. The displacement value can be obtained by a strain gauge, displacement meter, or extensometer that is fixed on a specified location of the specimen, but it can only measure the average displacement or that of a single point in one direction. As we know, different point have different displacement values even though they are in the same scale of the gage length, especially with a large deformation before necking occurs [4,5]. Therefore, we need a dynamic full-field measurement method to obtain the displacement accurately to evaluate the mechanical properties of metals.

Digital image correlation (DIC) [6–9] is an optical non-contact measurement method that uses cameras to capture many images during the whole deformation progress of an object. It is used to obtain the full-field deformation by comparing two speckle images before and after deformation based on gray correlation. Due to its advantages of convenient operation, minimal influence from the environment, full-field measurement and high precision, the deformation measurement system based on the DIC method is widely used in mechanical property testing. Feipeng Zhu [10] used the DIC method to analyze the plastic deformation of cylindrical specimens under a uniaxial tensile test. The results showed that two types of specimens entered the plastic state in different ways, but both of them maintained a constant deformation state. Zhang Yang et al. [11] utilized the digital speckle correlation method to discuss the anisotropy of SPCC steel, and the experimental results showed that the anisotropy of the flow stress is not obvious. However, the Lankford coefficient had a significant anisotropy, different from traditional methods that obtain only a constant Lankford coefficient, and its value decreased gradually with the increasing of deformation. Sun Tao et al. [12] introduced a

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deformation measurement system based on DIC to evaluate the mechanical performance of Cu/Al clad metals. The result demonstrated that the anisotropy of the Cu/Al clad metals' mechanical parameters first increased and then decreased with the increasing pre-strain. The plastic strain ratio and strain hardening rate strongly depended on the loading direction and pre-strain. SA Krishnan [13] studied the dispersion / localized necking phenomenon of a sheet subject to different strain rates by full-field deformation data based on DIC and then analyzed the metal flow and fracture behavior through the stress-strain field. Wang et al. [14] combined the DIC method with multi-cameras and measured the strain field of a sheet in the whole process of the cupping test. Giancane et al. [15] adopted the DIC method to study the shear properties of aluminum foam. Tang et al. [16] proposed a segmented matching method that modified the traditional digital image correlation method to obtain deformation strain of more than 450% for a polymer material. Hao Hu [17] put forward a method to measure a welding sheet with the DIC measurement system and TIG welding test. The dynamic measurement system obtained the sheet deformation law during the welding and cooling process.

Combined with conventional mechanical tests, the DIC method is successfully applied to the full-field and full-process deformation measurement of metal materials. It can obtain displacement field data to provide a reliable basis for determining the metal plastic deformation law and mechanism. In this paper, a dynamic full-field deformation measurement method based on 3D DIC technology was proposed for monitoring the uniaxial tensile deformation behavior of the high-strength low alloy steel H340LAD_Z. We focused on studying the plastic evolution in the yield stage of the sheet specimen and showed its anisotropy across three loading directions.

2. DIC method and experimental scheme

2.1. Key technology of DIC

The basic principle of the digital image correlation technique is shown in Fig. 1. In the un-deformed and deformed images, the speckle is digitized to produce codes to calculate the deformation. We select a square un-deformed subset of (2 M+1) ×(2 M+1) pixels centered at point (x_0, y_0) in the un-deformed image. Generally, in the deformed image, find the corresponding subset that has the greatest similarity to the un-deformed subset, and the point(x_0', y_0')in the center of the deformed subset is the corresponding deformed point. The other corresponding points can be obtained in the deformed images in the same way. For 3D DIC measurement, not only must sequence matching be performed on the deformed images captured by each camera, but stereo matching is also needed though the application of the triangulation principle algorithm to the inputs to two cameras. Finally, reconstruct the coordinates of the deformed points. The coordinate subtraction values of the deformed points and un-deformed points are the measuring point displacement. Repeat the above process to obtain the full-field displacement of the object surface.

During the process of image searching by DIC method, measure the similarity degrees between the non-deformed subset and deformed subset using the correlation coefficient. To complete the full-field image matching, the mapping function parameters are obtained by calculating the extreme values of the correlation coefficient. The sum of squared differences C_{SSD} [18,19] criterion is used to evaluate the similarity between the un-deformed subset and the deformed subset because of its insensitivity to gray linear changes and strong anti-interference ability.

$$C_{SSD} = \sum_{i=1}^{M} [f(x_i, y_i) - r_0 - r_1 \times g(x_i', y_i')]^2$$

where $f(x_i, y_i)$ and $g(x_i', y_i')$ are the gray values of point (x_i, y_i) in the un-deformed subset and point (x_i', y_i') in the deformed subset, respectively, and r_0 and r_1 are used to compensate the gray value difference caused by illumination variations.

2.2. Uniaxial tensile test

The uniaxial tensile test setup is shown in Fig. 2. Uniaxial tensile tests were conducted on an RGM4100 universal testing machine, and the tensile speed was set as 1 mm/min. An XJTUDIC measurement system, which was independently developed by our own laboratory was used to measure the full-field deformation of the specimen. The measurement system mainly includes two cameras (aca 1600–20 g, with a revolution of 1624×1236 pixels and a focal length of 8 mm), two LED lights, a control box, a computer, a post-processing system and other auxiliary equipment. The material used in present work was the high-strength low alloy steel H340LAD_Z, and the thickness was 1 mm. The chemical composition is provided in Table 1. The tensile specimens were cut along the rolling direction from one steel sheet by a wire-cutting process, and the cutting directions were 0°, 45° and 90°. The specimen dimensions are illustrated in Fig. 3. The gauge section of each tensile specimen was coated with black/white speckle, which met the requirement for the DIC algorithm [5]. A uniform coat of white

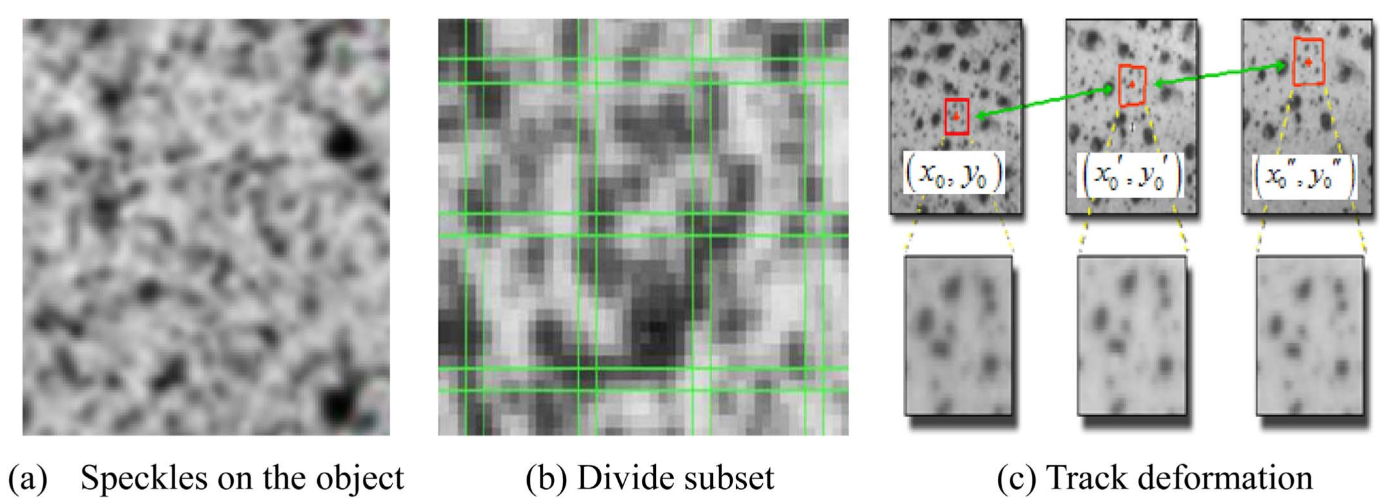

Fig. 1. Basic principle of the digital image correlation method. First, spray white/black speckles on the measured object surface, as shown in (a). The object deforms under an external load, and two cameras facing the object capture the whole deformation process with a certain frequency at the same time. Then, import the images into the post-processing software and set the subset size and step according to the accuracy requirement as (b). Finally, calculate the deformation displacement though tracking the gray correlation of the subsets, which is the key technology in the digital image correlation method as (c).