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Biaxial tensile testing of cruciform slim superalloy at elevated temperatures

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ABSTRACT

The stress–strain curves and yield loci of metallic materials under biaxial tensile tests can be precisely predicted using a yield criterion. In this study, biaxial tensile testing equipment with high-accuracy displacement, temperature control, and digital speckle correlation method of non-contact optical strain measurement is developed to study the thermo-mechanical deformation behavior of a GH738 nickel-based superalloy, which is widely used for important components of aeronautic engines, to exploit its excellent mechanical properties at high temperatures. Additionally, the used specimen shape is discussed. The results of this study show that the special sample shape size solves the problem in which an extremely thin sheet metal bulges when subjected to tension. The equivalent stress–strain curves and yield surfaces, which were fitted according to the Hill'48 yield criterion, exhibit deformation characteristics that are more precise than those according to the von Mises criterion. Eventually, the efficacy of the related test methods is corroborated.

1. Introduction

In recent years, sheet forming by thermoplastic processing, especially for aerial and spacecraft alloys, has been widely adopted. To reduce the design cost, the finite-element method has become an almost obligatory step to calculate the deformation of a sheet metal. The accuracy of these numerical simulations is contingent on the chosen constitutive model. By focusing on the prediction of the plastic behavior of metals in thermal environment, many investigations have been conducted using the MTS or Gleeble thermo uniaxial tensile testing machines [1, 2]. However, we have recognized that many sheet-forming processes are usually subjected to multiaxial loading conditions. Multiaxial stresses and strains cannot be detected by uniaxial tests. Using more realistic loading in an experiment will obtain a more accurate representation of the plastic deformation behavior of a sheet metal. Therefore, investigating the mechanical properties is required not only under uniaxial tension but also under these multiaxial states of stress, e.g., biaxial tension being close to actual physical scenarios. The biaxial-tension testing technique was first proposed by Shiratori and Ikegami [3]. Subsequently, many researchers (e.g., Kulawinski [4], Kuwabara [5], and Leotoing [6]) have developed biaxial tensile technology to study the properties of cold-rolled steel or Al alloy. In these works, this process was mostly achieved using independent hydraulic actuators that control the tensile axis displacement to actualize the deformation of a specimen pinched in a clamping chuck and using force sensor and strain gauge that measure the tensile force and strain, respectively. Even if these biaxial tensile technologies used mature mechanical devices applied at ordinary temperatures, they have to be considered valid for application implementation at high temperatures.

Only a small number of studies have applied this approach in high-temperature environments to date. A number of technical barriers have to be broken. First, as a common problem in the biaxial tensile technology, the specimen arm is fractured before the center section reaches the forming limit under normal stress. Increasing the deformation in the center section as far as possible is essential during the design according to the specimen thickness so that more effective data on the plastic-deformation stages are available to fit the stress–strain curves and constitutive model, consistent with the actual material properties. Second, with regard to the apparatus involved in high-temperature environment, Merklein and Biasutti and Terriault et al. have performed tensile testing of Al and Ti–Ni alloys, respectively, at elevated temperatures [7,8], whereas other thermal biaxial tensile techniques have also been applied to non-metallic materials. Merklein heated the specimen center section to 350 °C using a laser beam. The technology needs to consume large power. Terriault et al. set up a small biaxial tensile device in a thermo-environmental box. Because of the mechanical apparatus limitation, the experimental temperature only reached 60 °C. In the study of polyethylene terephthalate materials, Chevalier and Marco adopted an open thermo-environmental box [9], and the tiptop temperature reached 95 °C. These materials have a low phase-transition temperature, which proves that these technologies are sufficient for their studies. However, the temperatures used in the experimental techniques described in these studies are too low for application to metallic materials with excellent mechanical properties at high temperatures, e.g., nickel-based superalloys such as GH738. Third, although

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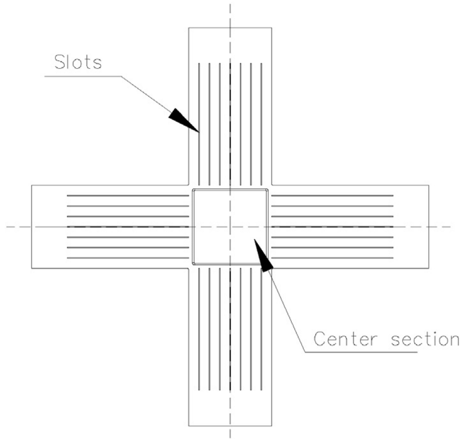

Fig. 1. Cruciform specimen with slots and thickness reduction.

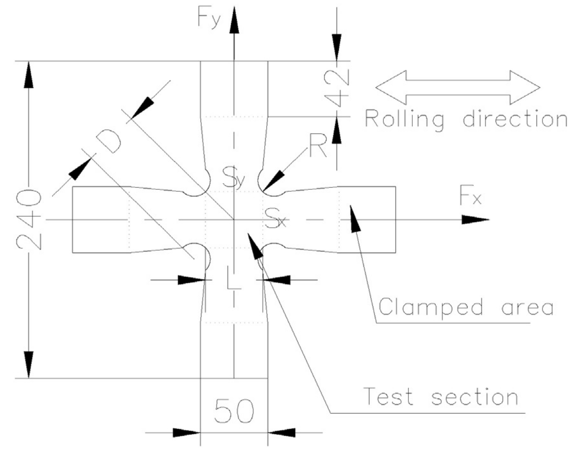

Fig. 3. Biaxial tensile specimen geometry.

strain gauge is widely used in various tests [10], many problems exist in high-temperature environment, e.g., limited measurement range, dramatically varying sensitivity with temperature, and so on. The issue of strain measurement also needs to be urgently solved. Finally, the use of correct yield criteria plays an important role in accurately describing material modeling. The process has to verify a valid yield criterion to be applicable at both room and elevated temperatures for GH738.

In this context, a new high-temperature biaxial tensile testing machine is developed, and a suitable specimen is designed, which attempt to obtain the equivalent stress–strain (σ–ε) curves and yield loci of GH738 at elevated temperatures using the biaxial tensile test at different stroke ratios and to compare them with the uniaxial tensile test results. The objective of the present work is to better understand the GH738 thermo-mechanical deformation behavior and plasticity evaluation under biaxial tension.

2. Cruciform specimen and equipment

2.1. Cruciform specimens

Many studies have investigated and discussed the appropriate shapes of cruciform specimens for biaxial testing, and the standard geometry for biaxial tensile specimens remains a topic of ongoing research. Two main design prerequisites emerged from the many research works: homogeneous distribution of the stress–strain in the center area and stress concentrations must be avoided in the arms [11]. For metal materials, the solution using slots in the specimen arms and thickness reduction at the test section appears to be have more adherents [12,13]. Fig. 1 shows this type of cruciform specimen. The thickness reduction in central section can prevent stress concentration and damage to the arms and can increase the deformation at the specimen center. Further, the presence of strips and slots in the arms reduces the effect of shear stress. However, this method requires sufficient specimen thickness (H). In this study, an H value of 0.25 mm only was utilized, which would result in frequent appearance of bubbles at the specimen center if the above design is employed. Further, Smits [14] and Lamkanfi et al. [15] have studied the effects of various values of corner filet radius R, which is located between the specimen arms, for optimized cruciform specimens. An increase in the circular groove at the corner area was proven to yield a σ distribution with greater uniformity and increased deformation in the central area, and premature arm fracture during experiment can be avoided.

For a specimen with the length (240 mm) and arm width (50 mm) recommended by the biaxial tensile test international standard ISO 16842-2014 [16], we used finite-element simulation to optimize the specimen geometry. A quarter of two-dimensional (2D) shell models were established using the pre-processing software HyperMesh. The calculation and post-process were done in ANSYS solver. Fig. 2 shows the calculation results. For model A, at a vertical corner, stress concentration caused by shear stress was generated, which could lead to tearing during the initial stage of the experiment. For model B, a convex filet played a similar role in the reinforcing rib, which decreased the strain in the central area. However, these disadvantages did not exist in model C, which is a concave corner.

Fig. 3 shows the dimensions of model C: $R = 12$ mm, and the distance from the arc center to the specimen center $D = 42$ mm. In the following discussion, we define the rolling and transverse directions as the X and Y directions, respectively. The length of the clamped area and the distance between adjacent arcs L are both 42 mm. We can calculate the cross-sectional areas of the components in the Y and X directions (S_y and S_x, respectively) using $L \times H$. Further, the forces in the X and Y directions, namely, F_x and F_y, are obtained using a force sensor. The

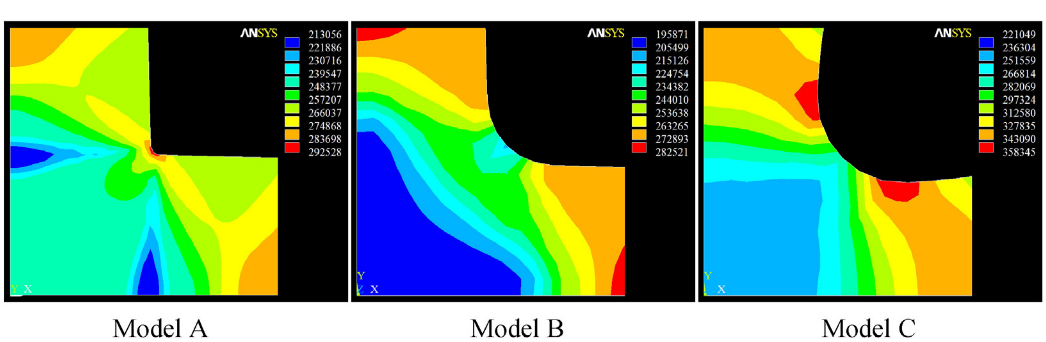

Fig. 2. Stress distribution of the specimen for the biaxial tensile test.