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Forming limit in thermal cruciform biaxial tensile testing of titanium alloy

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ABSTRACT

In this study, a new cruciform biaxial tensile testing technology was employed to evaluate the thermal limit strains of a TA1 titanium alloy, which is widely used as an aircraft structural component, so as to prevent fracture defects during thermoplastic processing. The effect of specimen shape on the forming limit and its measurement range is discussed. The results of this study show that a design that reduces the semispherical thickness results in localized necking and fracture at the center of the specimen when normal stress is applied to it. The forming limit diagrams obtained at different angles with respect to the material rolling direction suggested that the limit strain was anisotropic in nature. The experimental results were in good agreement with the substituted values obtained from the finite element analysis and Oyane ductile fracture criterion. Finally, the efficacy of the related test and prediction methods was corroborated.

1. Introduction

A forming limit diagram (FLD) is used to evaluate the strain (or stress) at the onset of localized necking of sheet metals under complicated loading. It is composed of two principal strains (or stresses obtained from different strain ratios tests) that act as the vertical and horizontal coordinates in a plane. Depending upon how the force is applied, FLDs can be commonly obtained by two biaxial tensile methods: one method uses a cylindrical flat punch to deep draw ("in-plane"), whereas the other uses a hemispherical punch to bulge ("out-of-plane"). In addition, sheet forming using thermoplastic processes such as hot stamping has been widely implemented. Kotkunde et al. (2016) reported the FLD for a Ti–6Al–4 V alloy in a thermal environment based on the bulging caused by a hemispherical punch. Unfortunately, such methods require changing the length-to-width ratios of specimens to obtain different strain ratios, which causes the experimental veracity to be narrowly related to the precision of the mold, thus making the process costly. Consequently, Yoshida and Kuwabara (2007) proposed tube expansion testing (also named hydroforming) to acquire the limit stress and strain of materials. However, the hot-pressure medium (e.g., oil or gas) hardly met the experimental temperature requirements for materials having a high phase-transition temperature, such as titanium alloys.

In this paper, a thermal cruciform biaxial tensile method is proposed to realize different strain ratio tests by changing the stroke ratios of the orthogonal axes. Hannon and Tiernan (2008) published a useful summary on cruciform biaxial tensile techniques, which widely used by researchers to investigate the plastic-deformation properties of materials. The test requirements are adhered to when the center section of the specimen reaches the plastic-deformation stage and a low strain level. However, in order to study the forming limit in the current study, the center section of the specimen needed to reach necking or fracture. Therefore, one of the most formidable technical barriers has been to address issues related to specimen design. Merklein et al. (2008) employed a laser beam to heat specimens, whereas Abu-Farha et al. (2009) applied a heat gun as an exterior heating device. However, these techniques result in defects similar to those found in hydroforming, and they fail to meet the temperature requirements. Kulawinski et al. (2015) was the only exception in this regard, as they investigated the effect of the multiaxial stress state on the fatigue life of superalloys in the temperature range of 400–650 °C via the isotropic theory.

To predict the sheet metal forming limit, Hill (1952) proposed the tensile instability theory, which was based on diffuse and localized necking. Stören and Rice (1975) determined the limit strains in the whole region of strain paths using a simplified constitutive model of a pointed vertex on subsequent yield loci. However, the predicted FLD does not always fit the measured values very well.

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Thus, Marciniak and Kuczyński (M-K) (1967) proposed the widely used damage instability and groove theory. The limit strains near the balanced biaxial tension predicted using the M-K analysis are extremely large as compared to those obtained experimentally. Tadros and Mellor (1978) later modified the M-K theory. Although these modifications have optimized the M-K theory, experimental verification suggests that the theory is expected to have a certain gap with the test results. Another hypothesis to predict the limit strain is the ductile fracture criterion, which is derived from deformation energy calculations and ductile damage models and is estimated by the macroscopic stress and strain during forming. Oyane et al. (1980) assumed that the history of hydrostatic stress played an important role in the occurrence of ductile fracture. On the basis of finite element simulations and hardening models, Takuda et al. (2000) successfully applied this criterion to the prediction of the forming limit of aluminum alloy sheets, although the value still needs to be verified at both room and elevated temperatures.

In this work, a special specimen was designed for investigating the forming limit. Xiao et al. (2016a,b) developed a new high-temperature biaxial tensile testing machine and a digital-image correlation (DIC) measurement system to conduct studies on the mechanical properties of nickel-based superalloys in previous study. The TA1 titanium alloy limit strains at elevated temperatures and different stroke ratios were calculated by using these technologies. The strains for localized necking were predicted by the combination of the finite element analysis and ductile fracture criterion. The objective of the present work was to evaluate the plasticity of TA1 and to determine its FLD at different temperatures.

2. Cruciform specimen

Many researchers have investigated the optimized shapes of cruciform specimens, including those used at elevated temperatures. However, the standard geometry remains a topic of ongoing research. The design prerequisite for the forming limit is a center-section fracture or necking of the specimen subjected to normal stress. Solutions using slots in the specimen arms and thickness reduction at the test section are reported to have more adherents. Based on this design concept, Zidane et al. (2010) investigated the forming limit of aluminum alloys. However, there is some skepticism regarding the determined values: first, as shown in Fig. 1, a convex fillet located between the specimen arms plays a role similar to that of a reinforcing rib, which lowers the strain level at the center section; second, based on finite element simulation and experiments, Xiao et al. (2016a,b) suggested that the failure originates at the endpoints of the slots close to the center area because of shear concentration and unavoidable small cracks caused by machining defects. Further, Smits et al. (2006) reported that a circular groove can increase the deformation in the central area and avoid premature arm fracture during experiments. Unlike other researchers, Ognedal et al. (2012) employed a semispherical thickness reduction of the central area. In the current study, the authors discussed the influence of the thickness reduction methods on stress distribution using finite element analysis. Kuwabara (2014) regulated the dimensions of the specimen standard, shown in Fig. 2, recommended by the biaxial tensile test international standard ISO16842-2014 with a length of 240 mm and a width of 50 mm. In the following discussion, the rolling and transverse directions are defined as the X and Y directions, respectively. The length of the clamped area was 42 mm.

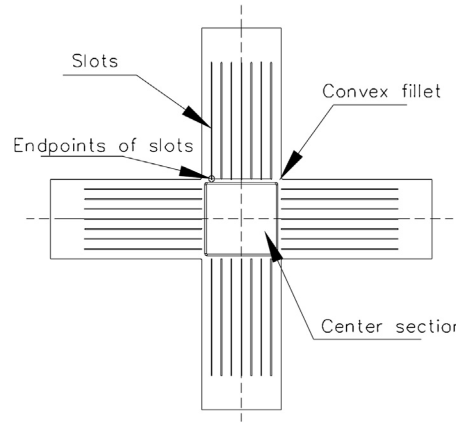

Fig. 1. Cruciform specimen with slots and thickness reduction.

A quarter-model with solid elements (SOLID164) with an edge length of 1 mm, a simulation time of 0.1 s, the von Mises yield criterion with an elastic modulus of 206 GPa, a Poisson ratio of 0.28, a yield strength of 145 MPa, and a tangent modulus of 5800 MPa was built using the pre-processing software HyperMesh. The calculation and post-processing were done in ANSYS solver. Fig. 3 shows the calculation results. For model A, the stress was concentrated at the border between the filleted corner and traditional straight surface, which resulted in premature fracture in this region. For model B, the stress was concentrated at the center area of the arc surface.

Because of the non-uniform thickness of the center area, some data of the nodes along the center line in the X direction were extracted in order to further verify the feasibility of model B and the location of the strain measurement in the test, as shown in Fig. 4, as a top partial viewport of the specimen center area. The distance between the adjacent nodes was uniform (1 mm). Node 0 and element (Ele.) 0 were located at the heart of the specimen. Fig. 5a shows the strain–time curves of nodes 0–5. At the beginning of the deformation, the elastic strain of every node showed a linear increase with similar values. With increasing plastic deformation, wide variations in the elastic strains were observed. The maximum

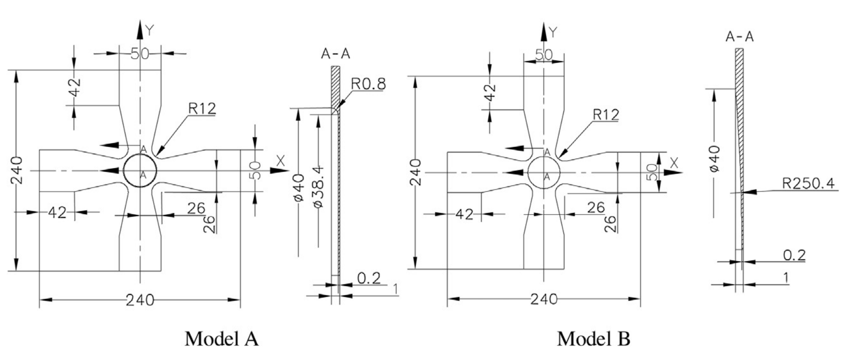

Fig. 2. Cruciform specimen with circular grooves.