

REVIEW PAPER**MULTIAXIAL STRESS TESTS FOR METAL SHEETS AND TUBES FOR ACCURATE MATERIAL MODELING AND FORMING SIMULATIONS**

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Received: 06.07.2014

Accepted: 14.11.2014

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Abstract

This paper is a review of the mechanical testing methods developed by the author's research group: multiaxial stress test methods using a cruciform test piece and a tubular test piece. The former is useful for small strain ranges under several percent while the latter is useful for larger strain ranges (from yielding to fracture). These test methods are useful to determine appropriate materials model for performing accurate metal forming simulations. Special attention is given to the measurement and modeling of the anisotropic plastic deformation behavior of sheet metals commonly used in industry and to the validation of the material models based on phenomenological yield functions for large plastic strain ranges. The effects of material models used in metal forming simulations on the improvement of the predictive accuracy for forming defects are also discussed.

Keywords: anisotropy; finite element analysis; formability; material model; mechanical test; sheet metal forming; yield function

1 Introduction

The establishment of trial-and-error-less manufacturing enhanced by forming simulation methods such as finite element analysis (FEA) is strongly desired in industry to shorten the product development period and reduce costs for prototype manufacturing. Improvement of the predictive accuracy for defect formation (such as fracture and springback) using FEA is key to realizing trial-and-error-less manufacturing. A material model is one of the key factors that affect the accuracy of FEA [1][2]. In metal forming processes, materials are subjected to multiaxial stress states and stress reversals. Therefore, the validity of the material models used in FEA should also be checked by multiaxial stress tests and stress reversal tests [3].

This paper reviews advanced material test methods for metal sheets and tubes to determine accurate material models for use in metal forming simulations. Special attention is given to the anisotropic plastic deformation behavior of lightweight metals, such as high-strength steels (HSS), aluminum alloys, and pure titanium sheets commonly used in industry, and to the validation of the material models based on anisotropic yield functions determined for large plastic strain ranges. Additionally, the effects of the material models on the improvement of the predictive accuracy of the forming simulations are discussed.

2 Biaxial tensile testing method using a cruciform test piece

2.1 Cruciform test piece

The biaxial testing of sheet metals can be performed by apply biaxial tensile forces to a cruciform test piece. Many types of cruciform test pieces have been proposed in literatures [1].

Fig. 1 (a) shows the cruciform test piece proposed by the author's research group [4]–[6]. Each arm of the test piece has seven slits to reduce the geometric constraint on the deformation of the square gauge area as much as possible. The arms are parallel to the RD and TD of a sheet sample. For fabrication of the test piece (including slit formation), laser or water jet cutting may be used. The RD, TD, and thickness direction of a rolled sheet metal test piece are defined in this paper as the x -, y -, and z -axes, respectively.

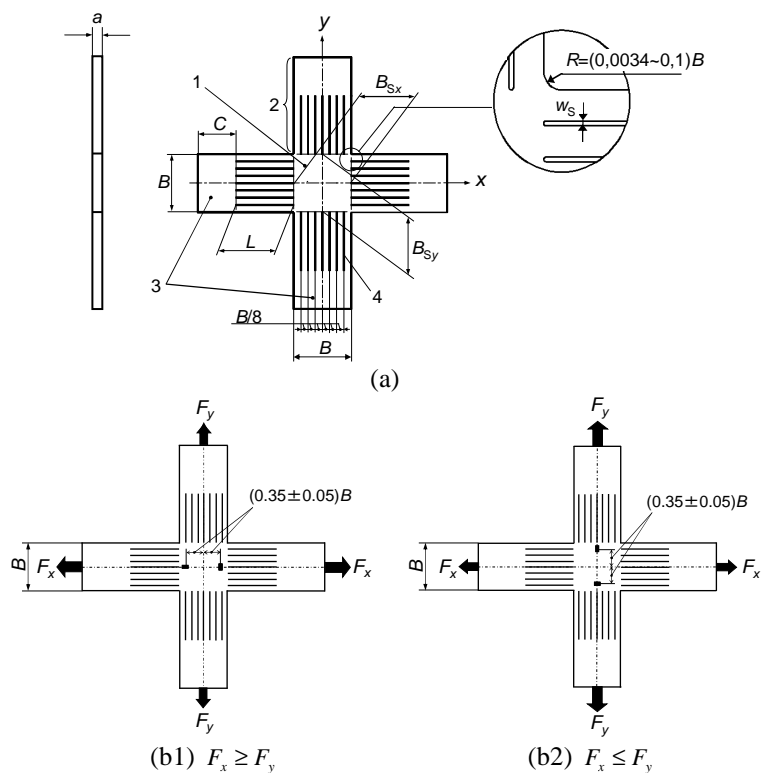


Fig. 1 (a) Cruciform test piece fabricated from flat sheet metal by laser cutting [4]–[6]. Recommended dimensions: $B \leq L \leq 2B$ (B : arm width, L : slit length), $t_0 \leq 0.08B$ (t_0 : sheet thickness), $N \geq 7$ (N : number of slits), $w_s \leq 0.01B$ (w_s : slit width) [7][8]. Here, a : thickness of test piece, B : arm width, B_{Sx} : distance between opposing slit ends in the x direction, B_{Sy} : distance between opposing slit ends in the y direction, C : grip length, L : slit length, R : corner radius at the junctions of the arms to the gauge area, w_s : slit width, 1: gauge area, 2: arm, 3: grip, and 4: slit. (b) Optimum strain measurement positions (■), where F_x and F_y are the tensile forces applied to the RD (x -axis) and TD (y -axis) of a sheet sample, respectively.

The normal strain components ($\varepsilon_x, \varepsilon_y$) should be measured at $(0.35 \pm 0.05)B$ from the center along the maximum principal stress direction, as shown in **Fig. 1** (b). According to FEA of the

cruciform test piece, using isotropic (von Mises) [7] and anisotropic yield functions [8] with the strain measurement position shown in **Fig. 1** (b), the stress measurement error becomes minimum and is estimated to be less than 2%. Consequently, supported by the numerical verification performed in [7] and [8], the cruciform test piece design and the biaxial tensile testing method have been established as an international standard [9]. Regarding the biaxial tensile testing machines proposed in literature, see [10].

It should be noted that the biaxial tensile test method using a cruciform test piece has proven to be useful for accurately detecting and modeling the deformation behavior of sheet metals under biaxial tension and consequently improves the predictive accuracy of FEA for springback in stretch-bending [11], hole expansion in HSS sheet [12][13], surface deflection in automotive body panels [14], and hydraulic bulge forming of 6000 series aluminum alloy sheets [15].

A cruciform test piece is useful for biaxial load-unload tests of sheet metals [16][17]. Successful FEA simulations of springback require suitable constitutive models that can capture the nonlinear strain recovery measured in these tests.

2.2 Application to a hole expansion simulation

The demand for HSS has been increasing for vehicle weight reduction in addition to crash performance improvement. In the press forming of HSS sheet, fractures frequently occur in stretch-flanging regions and cause serious problems in automotive body manufacturing [18]. In this section, a material modeling process based on the biaxial tensile tests using cruciform test pieces is shown for a 590 MPa grade HSS. In addition, the effects of the material models (anisotropic yield functions) on the predictive accuracy of FEA for hole expansion are clarified experimentally.

The initial hole diameter d_0 fabricated at the center of a circular blank was 30 mm, and the hole was opened using a wire electrical discharging machine. The periphery of the blank was clamped using a triangular drawbead at $\varnothing 190$ mm, see the figure attached to **Fig. 3**. The interface between the blank and punch head was lubricated with Vaseline and 0.3 mm thick Teflon sheet.

The material forming simulations of the hole expansion were performed using Abaqus/Standard Ver. 6.6-1. One quarter of a blank was analyzed due to orthotropic material symmetry. The reduced 4-node shell elements (S4R) with five integration points in the thickness direction were used for the blank. The punch, die, and blank holder were defined as rigid bodies. The coefficient of friction between the tool and blank was assumed to be 0. The displacement of the blank edge was fixed along the bead position at $\varnothing 190$ mm.

The material used was 1.2-mm-thick 590 MPa grade HSS (JSC590R). In order to determine an appropriate anisotropic yield function that is able to reproduce the elastic-plastic deformation behavior of the material, biaxial tensile tests were performed using the cruciform test piece shown in **Fig. 1** (a). The concept of the contour of plastic work in the stress space [19][20] was used to quantitatively evaluate the work-hardening behavior of the test material under biaxial tension. The stress-strain curve obtained from a uniaxial tensile test in the RD was selected as a reference datum for work hardening; the uniaxial true stress σ_0 and the plastic work per unit volume W_0 , which are associated with a particular value of true plastic tensile strain ε_0^p , were determined. The uniaxial true stress σ_{90} in the TD and the biaxial true stress components (σ_x, σ_y) were then determined at the same plastic work as W_0 . The stress points $(\sigma_0, 0)$, $(0, \sigma_{90})$, and (σ_x, σ_y) plotted in the principal stress space form a plastic work contour

associated with a particular value of ε_0^p . For a sufficiently small value of ε_0^p , the corresponding work contour can be practically viewed as a yield locus.

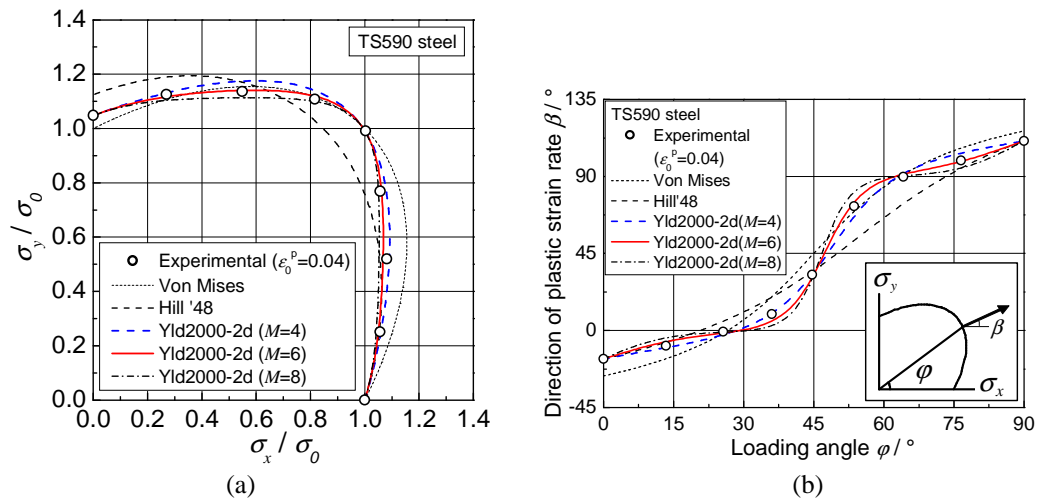


Fig. 2 Results of biaxial tensile tests [12]. (a) Measured stress points forming a contour of plastic work for $\varepsilon_0^p = 0.04$ compared with theoretical yield loci based on the selected yield functions. (b) Measured directions of plastic strain rates compared with those of the local outward vectors normal to the yield loci calculated using the selected yield functions. Here, ε_0^p is the uniaxial tensile plastic strain in the RD associated with W_0 .

Fig. 2 (a) shows the measured stress points that form the contour of plastic work for $\varepsilon_0^p = 0.04$. All stress values are normalized by the σ_0 associated with $\varepsilon_0^p = 0.04$. The figure also includes the theoretical yield loci based on the von Mises [21], Hill's quadratic [22], and Yld2000-2d yield functions [23][24] with exponents of 4, 6, and 8. The yield locus calculated using the Yld2000-2d yield function with an exponent of 6 has closer agreement with the work contour than the other yield functions.

In order to validate the normality flow rule for the selected yield functions, the directions β of the plastic strain rates were measured for all linear stress paths and compared with those calculated using the yield functions (the directions of the outward vectors normal to the theoretical yield locus). The results are shown in **Fig. 2** (b), where φ is the loading angle of the stress path from the x -axis in the principal stress space, and both β and φ are defined to be zero along the x -axis and positive in the counter-clockwise direction. The Yld2000-2d yield function with an exponent of 6 again provides the closest agreement with the measurement.

Fig. 3 shows the thickness strains measured along the hole edge at a hole expansion ratio of $\lambda = 0.244$, where $\lambda \equiv (d - d_0) / d_0$ (d : the hole diameter after the hole expansion test), compared with those computed using the selected yield functions. The Yld2000-2d yield function again provides the closest agreement with the experimental results. The predictive accuracy of Hill's quadratic yield function is inferior to that of the Yld2000-2d yield function.

From **Fig. 3**, the anisotropic yield functions were found to significantly affect the accuracy of the FEA for hole expansion. The Yld2000-2d yield function provided the closest agreement with the geometry of the work contour and the directions of the plastic strain rates measured using the biaxial tensile tests. Moreover, the Yld2000-2d yield function also provided the closest

agreement with the measured thickness strains along the hole edge. From these results, we conclude that it is necessary to determine an appropriate anisotropic yield function using biaxial tensile tests to improve the predictive accuracy of the hole expansion simulations.

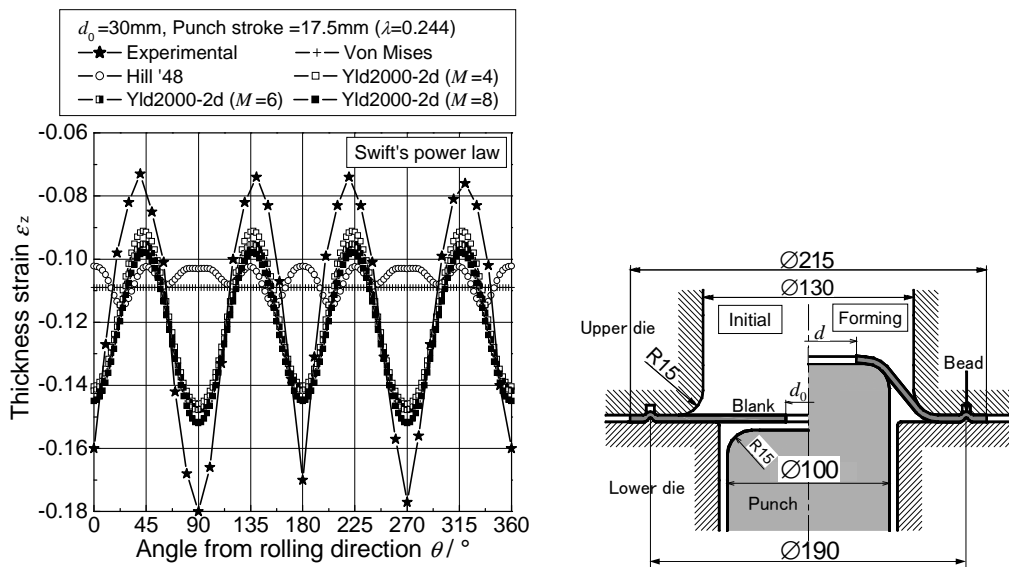


Fig. 3 Measured thickness strains along the hole edge compared with those calculated using the selected yield functions [12] (hole expansion ratio: $\lambda = 0.244$). The thickness strains were measured at locations approximately 1 mm from the hole edge.

3 Multiaxial tube expansion test for sheet metals

One of the drawbacks of the biaxial tensile test method using the cruciform test piece shown in Fig. 1 is that the maximum plastic strain applicable to the test piece is only several percent. In order to overcome this shortcomings of a cruciform test piece the author's research group has developed the multiaxial tube expansion test (MTET) method, which is useful for measuring the biaxial deformation behavior of tubular materials for a large strain range [25], [26], and forming limit strains and stresses [27], [28].

3.1 Testing machine

Fig. 4 shows a schematic diagram of the servo-controlled tension-internal pressure testing machine developed by the author's research group. An axial load T and an internal pressure P are applied to a tubular test piece by a hydraulic cylinder and a pressure booster, respectively, and the circumferential and axial strains ϵ_θ and ϵ_ϕ at the mid-section of the bulging test piece and the radius of axial curvature R_ϕ are measured simultaneously. The author has developed two strain measurement methods for a large strain range. One is that using displacement sensors [29] and the other is that using a digital image correlation (DIC) system [30]. The axial and circumferential stresses σ_ϕ and σ_θ at the mid-section of the bulging test piece can be calculated as the values at the mid wall using the equations based on the equilibrium requirements for a material element at the mid-section of a test piece [25], [26].

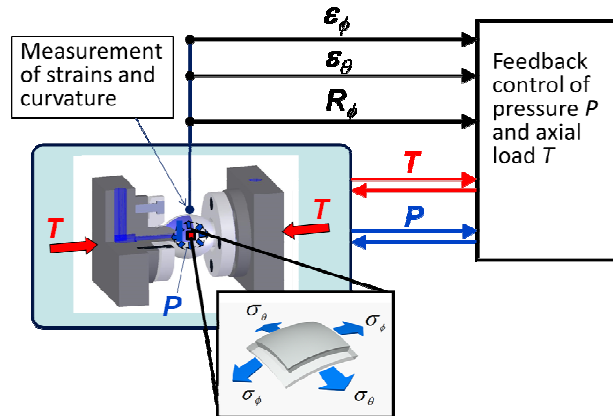


Fig. 4 A schematic diagram of the servo-controlled tension-internal pressure testing machine used for the MTET developed in [25] and [26]

3.2 Multiaxial tube expansion test for sheet metals

The author's research group has applied the MTET method to a tubular test piece that is made of a sheet sample to measure the biaxial stress-strain curves of the sheet metal for a large strain range for ultra-low carbon steel sheet [29], high-strength steel sheet [30], and pure titanium sheet [31][32], see **Fig. 5**. In addition, the forming limit strains and stresses of sheet metals were successfully measured [29], [30]. Tubular test pieces were fabricated by bending sheet samples into a cylindrical shape and laser welding the sheet edges together.

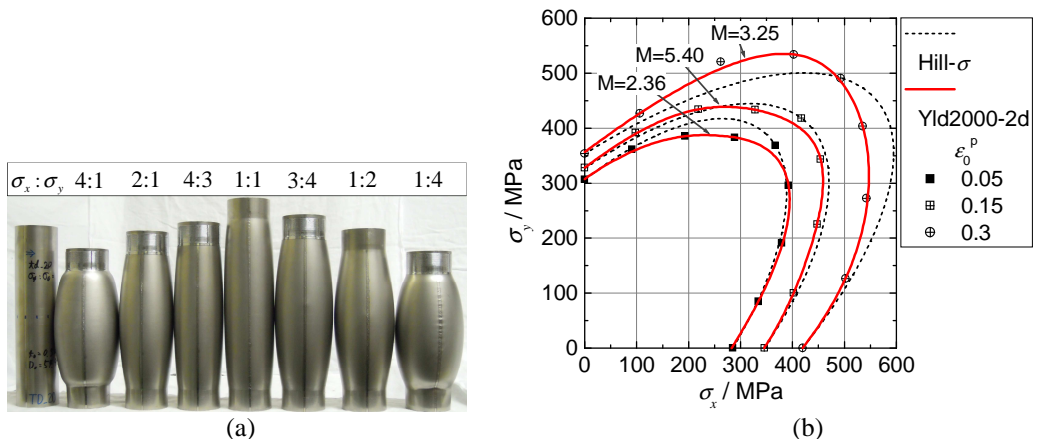


Fig. 5 Experimental results of the MTET for a JIS #1 pure titanium sheet [32]. (a) Fractured test pieces (the direction of the maximum principal stress is in the circumferential direction). (b) Measured stress points forming contours of plastic work compared with the theoretical yield loci based on selected yield functions.

3.3 Measurement and analysis of forming limit strains and stresses for sheet metals

Fig. 6 (a) shows the measured stress points forming contours of plastic work. It was found that the plastic work contours change in shape with increasing ϵ_0^p ; the material exhibited differential

work hardening (DWH). Also depicted in the figures are the theoretical yield loci based on the Yld2000-2d yield function [23][24]. The DWH behaviour was approximated by changing the material parameters α_i ($i=1\sim 8$) and exponent M of the Yld2000-2d yield function as a function of ε_0^p , as shown in Fig. 6 (b). The yield loci calculated using the Yld2000-2d yield function are in good agreement with the measurement for respective values of ε_0^p .

Fig. 7 shows the forming limit strains and stresses measured using the MTETs, hydraulic bulge tests, and uniaxial tensile tests. For the FLC and FLSC calculations based on the M-K approach, the Yld2000-2d yield function for $\varepsilon_0^p = 0.35$ with the isotropic hardening (IH) assumption and the DWH model, as shown in Fig. 6, were used. The magnitude of initial imperfection, the strain rate sensitivity exponent (m-value), and the equivalent plastic strain rate were assumed to be 0.995, 0.02, and 0.0005 s^{-1} , respectively. The calculated FLC and FLSC based on the DWH model have a closer agreement with the experimental data than those based on the IH model. Thus, it is concluded that the DWH model is an effective material model for improving the accuracy of the forming limit predictions. See [35] for the details of the constitutive equations to calculate the DWH model. The calculation procedures for the M-K approach are described in [36].

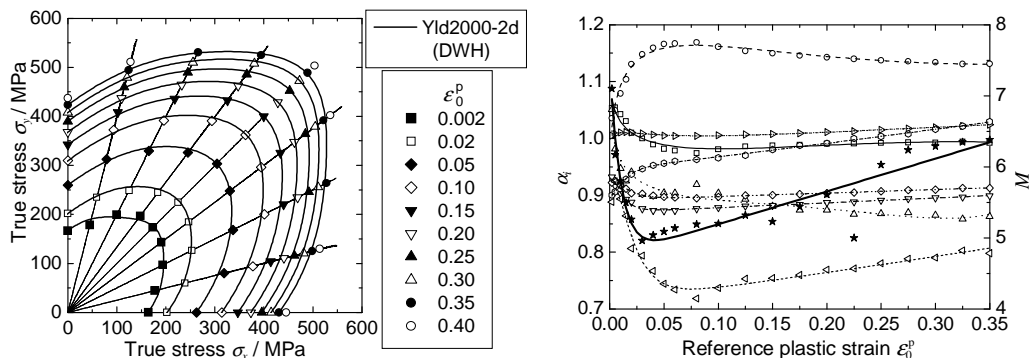


Fig. 6 (a) Measured stress points forming contours of plastic work, compared with those calculated using the Yld2000-2d yield function with differential work hardening (DWH). Material: 0.7-mm-thick cold-rolled IF steel sheet. (b) Variation of the material parameters α_i ($i = 1\sim 8$) and exponent M of the Yld2000-2d yield function with increasing ε_0^p . [33]

4 Other Multiaxial Test Methods

A test method for applying combined tension-shear stresses to a sheet specimen has been proposed in [37]–[39]. Low, intermediate and high strain rate tensile experiments were carried out for DP590 and TRIP780 steel sheets using flat smooth, notched and central-hole tensile specimens to investigate the effect of strain rate on ductile fracture [40].

5 Conclusions

Multiaxial stress tests using cruciform test pieces and tubular test pieces are powerful experimental methods for determining and validating material models used in forming simulations. They enhance the predictive accuracy for forming defects such as fracture and springback. In particular, the MTET method is of crucial importance for measuring the multiaxial plastic deformation behavior of metal sheets and tubes for a large strain range.

Moreover, it is useful to precisely determine the forming limit strains and stresses of metal sheets and tubes subjected to linear and nonlinear stress/strain paths.

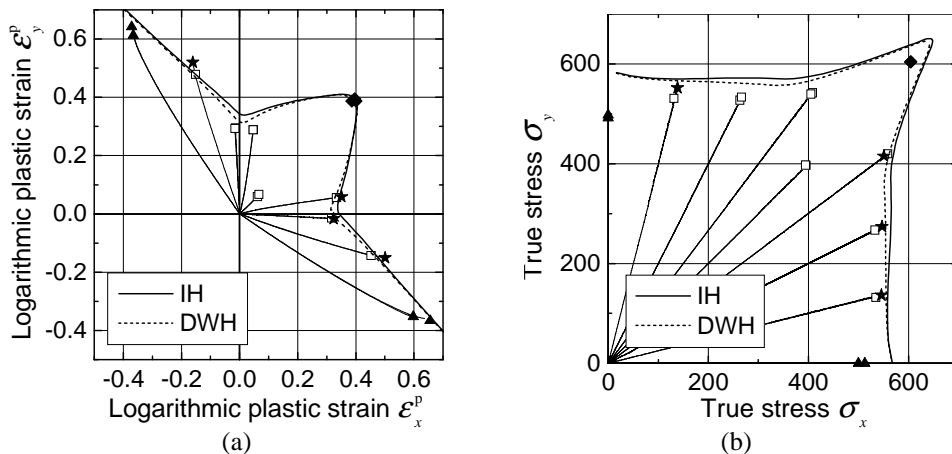


Fig. 7 (a) Forming limit strains and (b) forming limit stresses. The solid and dashed lines are those calculated using the M-K approach. \square : Fractured at a position of $\theta \leq \pm 30^\circ$ (where θ is the angle from the weld line in the circumferential direction of a tubular test piece), \blacklozenge : hydraulic bulge test, \star : fractured at a position of $\theta > \pm 30^\circ$, and \blacktriangle : Uniaxial tensile test. [33]

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