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Rope-driven biaxial tensile testing apparatus with specified load ratio

TAKIZAWA Hideo[1,a] *, FUJIYA Kazuto[2]

[1]Department of Mechanical Engineering, Nippon Institute of Technology, 4-1 Gakuendai, Miyashiro-machi, Saitama, 345-8501, Japan

[2]Graduate student, Graduate School, Nippon Institute of Technology, ibid., Japan

[a]htaki@nit.ac.jp

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Abstract. A novel biaxial tensile apparatus that can be installed on a universal testing machine is proposed. A tensile load was applied using a looped rope and pulley. The biaxial load can be changed by varying the angle of the rope hanging on the movable pulleys, and the ratio of the biaxial tensile force can be specified. A small cruciform specimen with a stress evaluation area of 12.5 mm square was used for preliminary tests. Biaxial tensile tests were conducted on mild steel sheets to measure the stress points on the contours of equal plastic work. A comparison with the yield surface measured using a standard biaxial tensile testing machine revealed that biaxial tensile tests using the proposed method can be performed appropriately.

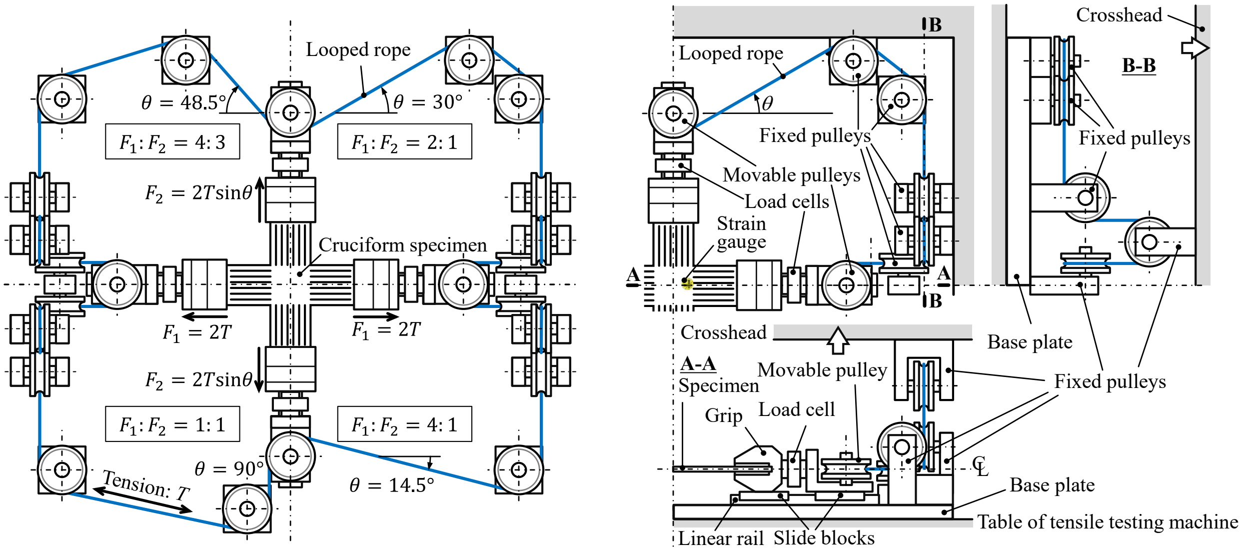
Introduction

To improve the accuracy of sheet metal forming analysis, an anisotropic yield surface can be modeled based on the results of material tests in a biaxial stress state. A biaxial tensile test using a cruciform specimen was standardized by ISO 16842:2021 [1]; however, a specialized and expensive testing machine was required to load a constant biaxial stress ratio [2,3,4].

To address this issue, Ferron et. al. [5], Nagayasu et. al. [6], and Merklein et. al. [7] developed an apparatus that could be installed in a general-purpose tension-compression testing machine. These apparatuses were designed to be loaded at a constant biaxial displacement ratio using a link mechanism. Using this type of apparatus, the ratio of the tensile displacement of the arms of the cruciform specimen can be modified by recombining the link mechanism. However, in the case of biaxial plastic deformation, the histories of the strain and stress paths generally differ depending on the cases of constant displacement, strain, and stress ratios. The yield surface, which can be measured using a biaxial tensile test with a constant displacement ratio, is limited to a stress state close to equibiaxial stress.

In this study, we present the concept of a novel biaxial tensile testing apparatus driven by pulleys and looped rope and report preliminary measurements of the yield surface (stress points on the contour of equal plastic work) of mild steel using the proposed apparatus. The measured stress points were compared with the yield surface modeled by a standard biaxial tensile testing machine.

Outline of proposed apparatus

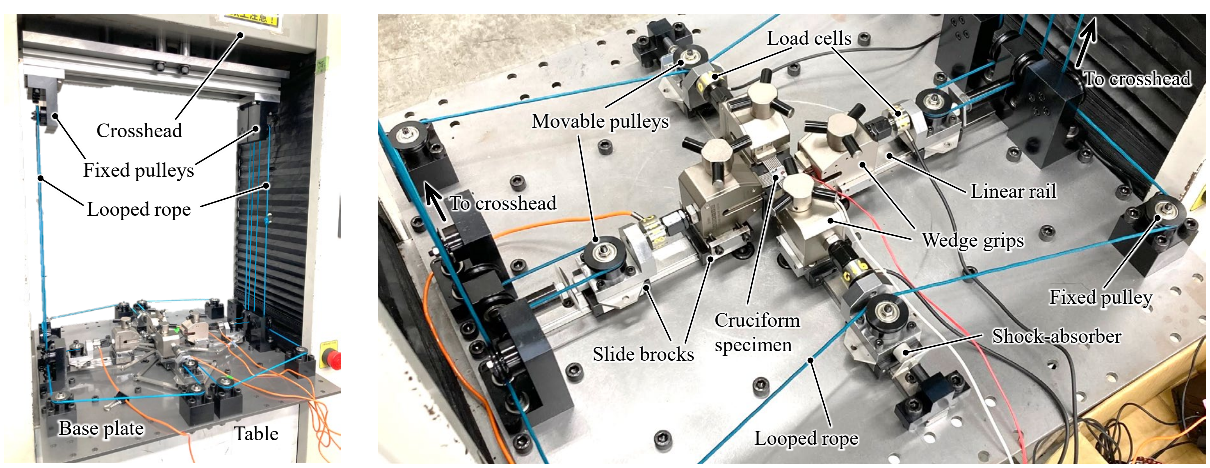


(a) Pulley positions for 4 types of tensile force ratios (b) Detailed assembly of tensile unit

Fig. 1 Schematic for proposed biaxial tensile testing apparatus using a looped rope and pulleys, installed in conventional uniaxial tensile testing machine.

Fig. 1 shows the configuration of the proposed biaxial tensile apparatus. As shown in Fig. 1(a), a cruciform specimen was placed at the center of the apparatus, and a tensile load was applied from the top, bottom, left, and right of the figure. The first to fourth quadrants of the figure show the test configurations for different load ratios of $F_1 : F_2$ = 4:1, 2:1, 4:3, and 1:1.

On the central side of each tensile axis, the tensile grip can freely move along the linear rail on the axis, as shown in Fig.1(b). A load cell and movable pulley are connected to the back end of the grip. In this apparatus, the rope was hung on a movable pulley on a linear rail, and the tensile load on each axis was applied by the rope tension. Because the rope was single and looped, the tensile force generated in the rope was constant at all positions on the rope. In the left and right axes in



(a) Installed in general purpose tensile testing machine (b) Detail testing section, biaxial tensile mechanism ($\theta = 14.5°$, $F_1 : F_2 = 4:1$)

Fig. 2 Photograph of prototype biaxial tensile apparatus installed in general purpose tensile testing machine.

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Fig. 1(a), the rope under tension is parallel to the tensile axis, and in the top and bottom axes, the rope is hung on the movable pulley with the angle θ specified by the positions of the fixed pulleys. Consequently, the ratios of the left and right loads F_1 and the top and bottom loads F_2 acting on the cruciform specimen are

$$F_1 : F_2 = 1 : sin\theta. \quad (1)$$

In this apparatus, the load ratio of the biaxial tension can be arbitrarily set by determining the path of the looped rope based on the positions of the fixed pulleys on the base plate. In addition, please note that in this explanation the change in angle θ due to slight deformation of the specimen and the friction of the pulleys are ignored.

A photograph of the prototype apparatus is shown in Fig. 2. As shown in Fig. 2(a), the base plate of the apparatus is fixed to the table of a general-purpose tensile-testing machine (Autograph AG-100kN, Shimadzu Corporation). The looped rope was hung on four pulleys fixed to the bottom face of the crosshead, and a tensile load was applied to the rope by raising the crosshead. The rope was made of high-strength fibers (Vectran SV-26), and the maximum test load of the biaxial tension was designed to be 5 kN, based on the strength of the tied rope. Fig. 2(b) shows an enlarged image of the test section. Wedge grips with 5kN capacity (MARK-10 G1061) were used in four directions.

Test material and testing conditions

To evaluate the validity of the measurement using the proposed apparatus, specimens were cut from an identical lot of mild steel sheets, which yield surface (contour of equal plastic work) was measured with a standard biaxial tensile testing machine by Kuwabara et. al. [8]. The test material is an SPCD (equivalent to ISO 3574 CR2 steel) with a nominal thickness of 1.0 mm.

The dimensions of the cruciform specimen specified by ISO 16842 [1,9] were reduced to a small size with a stress evaluation area of 12.5 mm square and cut by fiber laser processing. However, the 0.15 mm width of the slits on the arms was relatively large for the small specimen, and the strength of the arm to apply a tensile load was insufficient. Strain was measured using the smallest biaxial strain gauge (TML, FCAB-1) attached to a specified position in the stress evaluation area of the specimen.

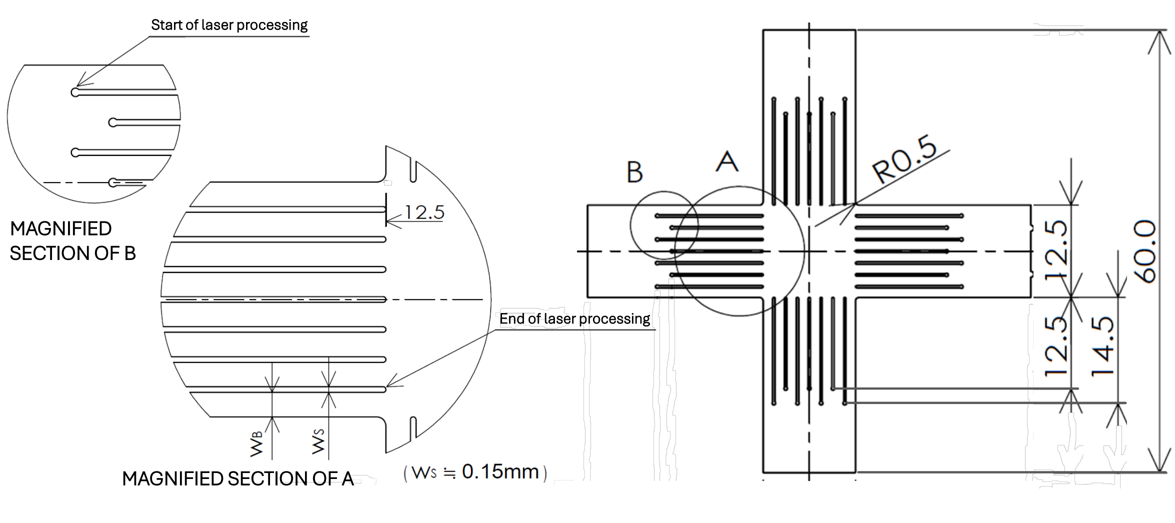


Fig. 3 Dimensions of small cruciform specimen with 12.5mm square stress evaluation area.

The stress ratio was set to σ_x: σ_y= 4:1, 2:1, 4:3, 1:1, 3:4, 1:2, and 1:4 as the stress in the rolling direction (RD) σ_x and transvesal direction (TD) σ_y, respectively. For a stress ratio of σ_x: σ_y=1:1, experiments were conducted in which the RD and TD were swapped between the horizontal and vertical axes of the testing apparatus.

Results and Discussions

Fig. 4 shows the true stress-true plastic strain curves obtained using the proposed biaxial tensile apparatus. The graphs in the upper row show the results of the experiment in which the RD of the sheet metal was parallel to the F_1 axis of the apparatus, and the lower row shows the results in which the TD was parallel to F_1.

The curves represent the results of three experiments under each condition. Because a small specimen was used, the variations in the measured stress-strain curves were significant even under the same conditions; however, the tendency of the experimental results was consistent.

Based on the specific plastic work obtained by integrating the true stress-true plastic strain curve, the stress points on the contour of the equal plastic work were determined. The magnitude of plastic work is shown as the reference plastic strain, which is the tensile plastic strain of the RD uniaxial tension.

Fig. 5(a) shows the validation of the linearity of the stress paths of the proposed apparatus. Broken lines indicate the intended stress paths. The experimental stress paths of the solid line run along the intended line. The biaxial tensile tests with almost constant stress ratios have been achieved.

Fig. 5(b) shows the experimentally measured stress points. The stress points were limited to a maximum reference plastic strain of 0.03 due to the early fracture of the arms. The curves in the figure show the yield loci measured with a standard biaxial tensile testing machine with hydraulic power and modeled by Kuwabara et. al. [9] using Yld2000-2d. The stress points measured using the proposed apparatus are close to the reference yield surface.

The stress points measured in this experiment are slightly higher than those of the reference yield loci. Because the size of the specimen was very small, variations in the dimensions of the

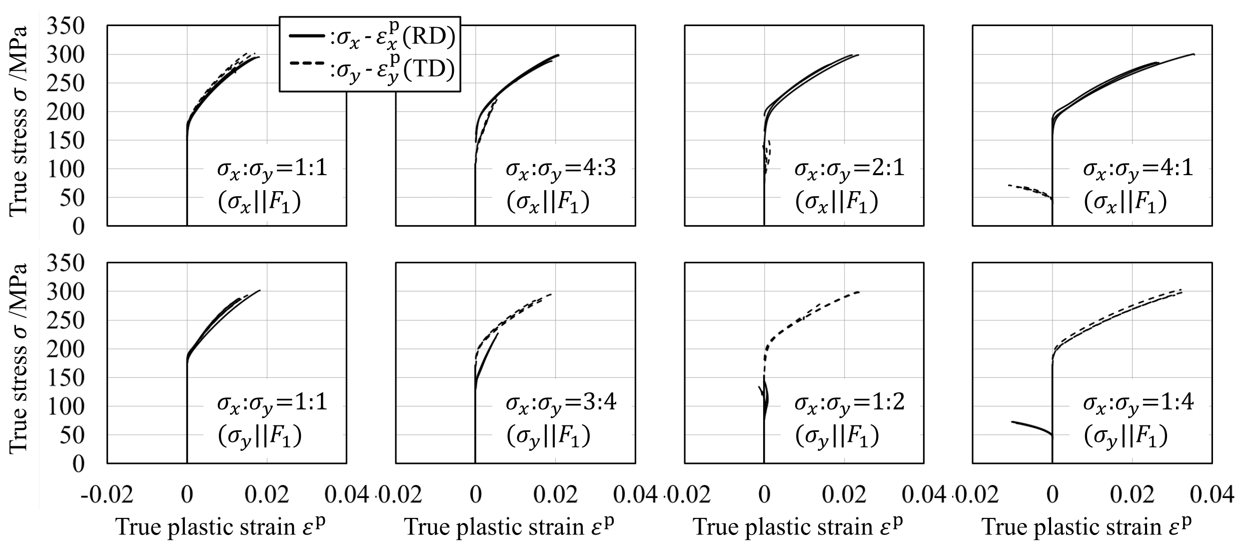
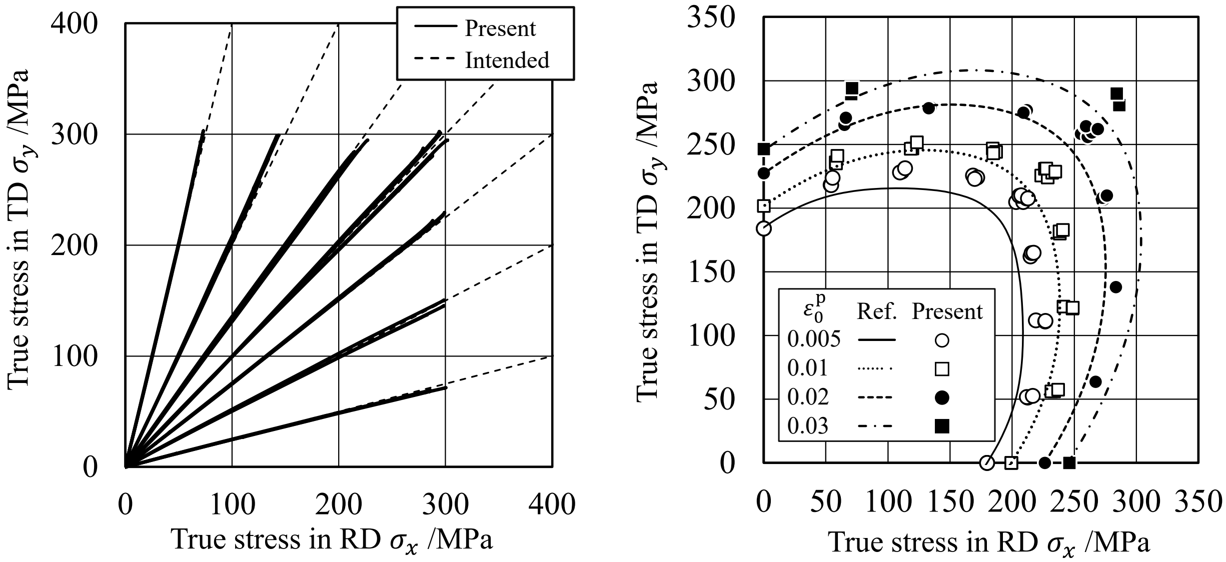


Fig. 4 True stress-true plastic strain curves measured by prototype of proposed biaxial tensile testing machine (upper: RD is parallel to axis, lower: TD is parallel to axis)

specimen significantly affected the measured stress. More accurate processing of specimens is required in the future.



(a) Intended stress path and experimental path of proposed apparatus

(b) Stress points on contours of equal plastic work measured using proposed apparatus and with referenced yield loci

Fig. 5 Experimental results using proposed apparatus, (a) validation of stress ratio, (b) comparison with yield loci modeled using standard biaxial tensile testing machine.

Conclusion

We developed a novel biaxial tensile testing apparatus that uses the transmission of a tensile load by a looped rope and conducted a biaxial tensile test on a mild steel sheet for preliminary testing. Although certain accuracy problems were observed, it was confirmed that the biaxial test could be performed at the intended load ratio. In the future, improvements will be made for its practical use as an efficient and reasonably priced apparatus for biaxial tensile testing.

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