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A new technique for characterising mechanical properties of materials under hot stamping conditions

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Abstract. In order to characterise mechanical properties of materials (e.g. formability) under hot stamping conditions, significant efforts have been made to the development of the biaxial tensile testing method using cruciform specimens. However, no method for necking strain determination and no cruciform specimen design have been widely accepted. In this study, a new technique for characterising mechanical behaviour of materials under hot stamping conditions has been proposed. It includes two main parts: 1) a novel spatio-temporal method for determining necking and fracture strains, and 2) a cruciform specimen design for formability evaluation using biaxial testing method. In the first part, the theoretical base of the novel spatio-temporal method has been discussed, and the method has been validated by applying to uniaxial tensile tests on AA6082 specimens. The method has also been compared with several existing popular methods, in the determination of limit strain at onset of localised necking. It is found that the novel method has greater simplicity, stability and accuracy for the determination of localised necking strain. In the second part, a proposed cruciform specimen of AA5754 has been tested under the equi-biaxial tension, and both the necking initiation location and the strain path at the location where necking initiates, have been analysed. Furthermore, the novel spatio-temporal method has been applied to the biaxial tensile test for the determination of necking and fracture strains. The results show that the designed cruciform specimen enables to initiate fracture at the centre of the specimen and realisation of linear strain path under equi-biaxial tension.

1. Introduction

Hot stamping technologies have been widely applied to sheet metals for producing high strength complex-shaped engineering components [1,2]. Both application and optimisation of those technologies require a profound characterisation of mechanical properties (e.g. formability) under hot stamping conditions. Due to the complex temperature profile experienced by workpieces in hot stamping processes, the conventional tests, such as Nakajima and Marciniak tests, are particularly difficult to be used for formability evaluation under those extreme conditions [3]. It has been shown that biaxial tensile testing method using cruciform specimens has high potential to overcome this difficulty [4].

Formability evaluation using the biaxial tensile testing method usually requires three main parts: 1) a mathematical method for limit strain determination, 2) a biaxial tensile testing machine and 3) cruciform specimens with a suitable design. This study mainly focuses on the limit strain determination method and the cruciform specimen design. So far, many mathematical methods for limit strain determination have been developed and utilised. One of the most famous methods is the cross-section method provided in the standard ISO 12004-2:2008 [5]. Other methods include the linear



best fit method [6] and the coefficient correlation method [7], etc. However, all those methods have their own limitations and disadvantages, which impedes their applications to biaxial tensile tests [8]. In respect to the cruciform specimen designs, the standard ISO 16842:2014 [9] provides a recommended cruciform test piece, but it is used for yield surface measurement rather than formability evaluation. Apart from this, many cruciform specimen designs have been proposed and tested [10], and a review of those existing cruciform specimen designs has been made in [11]. However, no one design has been widely accepted for formability evaluation so far.

This study aims to develop the biaxial tensile testing method for formability evaluation for materials under hot stamping conditions. A previously proposed spatio-temporal method for determination of necking and fracture strains, and cruciform specimen for formability evaluation, were analysed and discussed. The theoretical base of the spatio-temporal method was derived. Furthermore, the method validation was performed by applying to uniaxial tensile tests on AA6082 specimens. The spatio-temporal method was also compared with several popular existing methods, in respect of the values of the determined limit strain at onset of localised necking. Equi-biaxial tensile tests were carried out on AA5754 cruciform specimens, and both the necking initiation location and the corresponding strain path were analysed. Finally, the spatio-temporal method was applied to the biaxial tensile tests for the determination of necking and fracture strains.

2. Novel spatio-temporal method

2.1. Theoretical base

A novel spatio-temporal method has been proposed for determining necking and fracture strains by analysing average thickness reduction/major strain within two rectangular zones RZ and BZ [8]. In this study, average thickness strain is used for limit strain determination. Figure 1 shows the selection of the zones RZ and BZ around the necking initiation location, and their dimensions. The areas of the zone RZ, the zone BZ and the zone RZ excluding the zone BZ are designated as A_{RZ} , A_{BZ} and A_{RZ-BZ} , and the corresponding thickness strain increments within these zones are $\Delta\epsilon_3^{RZ}$, $\Delta\epsilon_3^{BZ}$ and $\Delta\epsilon_3^{RZ-BZ}$, respectively.

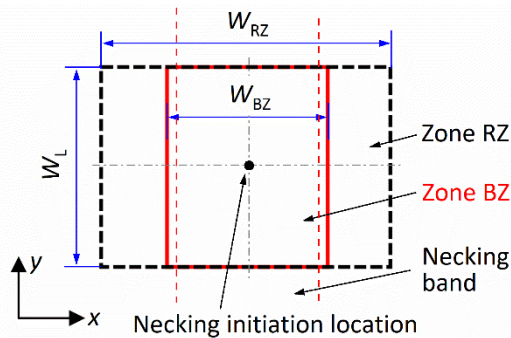


Figure 1. Schematic diagram showing selection of zones BZ and RZ for determination of necking and fracture strains using the spatio-temporal method. Note that zones RZ and BZ have same centre and dimension W_L , and zone RZ includes zone BZ.

From the start and during homogeneous deformation, the average thickness strain within the zone RZ and the zone BZ is theoretically the same. Therefore,

$$\Delta\epsilon_3^{RZ} = \Delta\epsilon_3^{BZ} \quad (1)$$

After the onset of localised necking, deformation concentrates in the necking band and $\Delta\epsilon_3^{RZ-BZ} = 0$. Thus,

$$\Delta\epsilon_3^{RZ} = \frac{\Delta\epsilon_3^{RZ-BZ} \times A_{RZ-BZ} + \Delta\epsilon_3^{BZ} \times A_{BZ}}{A_{RZ-BZ} + A_{BZ}} = \Delta\epsilon_3^{BZ} \times \frac{A_{BZ}}{A_{RZ-BZ} + A_{BZ}} \quad (2)$$

Although the area A_{BZ} continues to increase slightly, the area A_{RZ-BZ} does not change because of the localised necking. Hence, the strains $\Delta\epsilon_3^{RZ}$ and $\Delta\epsilon_3^{BZ}$ also keep an almost linear relationship. This

is the theoretical base of the spatio-temporal method to determine the onset of localised necking by fitting two straight lines in stable and instable deformation separately [8].

In order to enable that the line fitting is independent on testing speed and frame rate for strain measurement, the first straight line is fitted using the experimental points during the time range of $0 \sim t_S$, and the time range of $t_{IS} \sim t_F$ is used for fitting the second straight line, where t_F is time at fracture. The values of t_S and t_{IS} are recommended in Table 1, together with other recommended values for the dimensions in Ref. [8]. It should be noted that at least three experimental points are required for fitting the lines.

Table 1. Recommended values for the determination of necking and fracture strains using the spatio-temporal method, h and t_F are material thickness and fracture time, respectively

Items	Recommended values
W_{BZ}	$a \times h, a = 2 \sim 2.5$
W_{RZ}	$b \times W_{BZ}, b = 2 \sim 2.5$
W_L	$c \times h, c = 1.5 \sim 3$
t_S	$d \times t_F, d = 0.3 \sim 0.5$
t_{IS}	$e \times t_F, e = 0.990 \sim 0.998$

2.2. Method validation

The spatio-temporal method was validated by applying to uniaxial tensile tests on 1.5 mm thick aluminium alloy AA6082 sheet. Dog-bone shaped specimens, with a parallel length 34 mm and a width 6 mm in the reduced section, were cut along the rolling direction of the as-received sheet with T6 temper. The uniaxial tensile tests were carried out at room temperature with a constant tensile speed of 15 mm/min. The digital image correlation (DIC) technique was used for strain measurement, and a constant frame rate 125 fps was adopted for recording deformation. The commercial software GOM correlate 2018 was utilised for data post-processing, setting up with a facet size of 19 pixels and a point distance of 5 pixels.

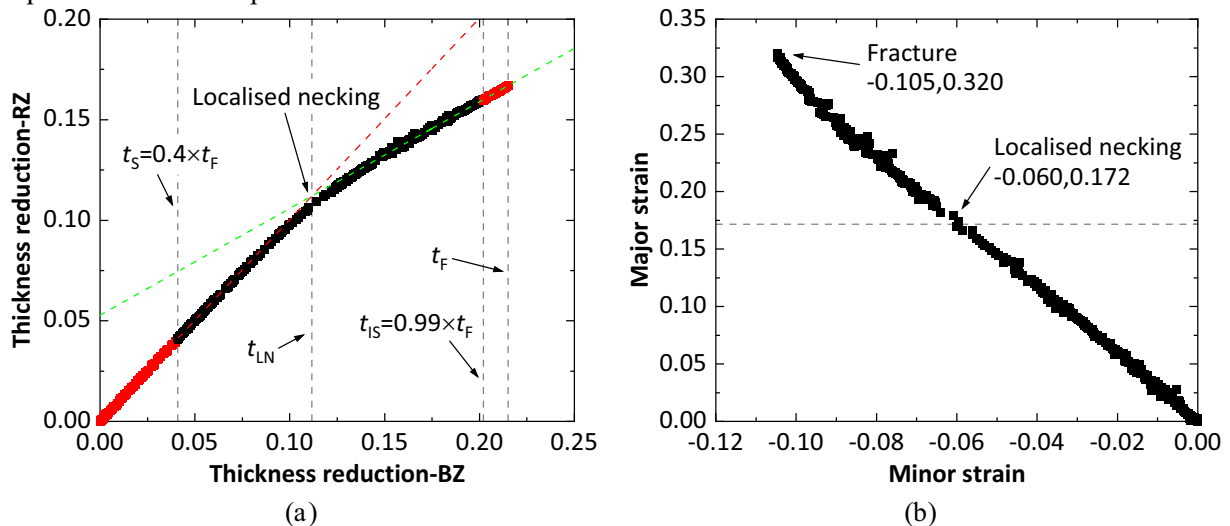


Figure 2. Validation of the spatio-temporal method for the determination of necking and fracture strains in uniaxial tensile tests on 1.5 mm thick AA6082 sheet, (a) determined onset of necking and fracture, (b) determined necking and fracture strains.

Figure 2(a) shows the determination of onset of localised necking and fracture using the spatio-temporal method, by adopting the following values as recommended in table 1, $a = 2$, $b = 2$, $c = 2$, $d = 0.4$, and $e = 0.99$. In the figure, the red points were selected for fitting the dashed green and red lines, representing stable and instable deformation, respectively. Indeed, different linear relationships exist

between $\Delta\epsilon_3^{RZ}$ and $\Delta\epsilon_3^{BZ}$ before and after the onset of localised necking. Moreover, the recommended values of the time t_S and t_{IS} are reasonable for the line fitting. Based on the determined onset of necking and fracture, the corresponding limit strain was determined, as shown in Figure 2(b). The determined necking strain is (-0.06, 0.172) and the fracture strain is (-0.105, 0.32). In addition, the strain path is linear and is maintained throughout deformation. It can be observed that ratio of minor strain to major strain is about -0.34 rather than -0.5, which demonstrates the anisotropy of the material.

2.3. Comparison with existing methods

The spatio-temporal method was compared with several popular existing methods, in the determination of limit strain at onset of localised necking. Those existing methods include cross-section method (CS) [5], linear best fit method (LBF) [6], correlation coefficient method (CC) [7], gliding correlation coefficient method (GCC) [12], and gliding difference of mean to median method (GMM) [12]. By using a script implemented in the commercial software ARAMIS, the existing methods were successfully applied to limit strain determination in the uniaxial tensile tests on AA6082 specimens. Figure 3 shows a comparison of the determined necking strains by using the existing methods, and the necking and fracture strains by using the spatio-temporal method. For the CS method, five different sections were selected and thus, five different values of necking strain were determined. Furthermore, all the determined limit strains have a same ratio of minor strain to major strain, and thus, only the major strain was compared for the limit strain comparison. The determined major strain at onset of necking by using the spatio-temporal method is almost the same as that by using the CS method and the CC method, while it is much smaller than that determined by using the LBF method, the GCC method and the GDMM method. Specifically, the spatio-temporal method determined a major strain 0.172, which is 48.4% smaller than 0.333 by using the LBF method. It is noticed that the values of the major strain at necking, determined by using the LBF method, the GCC method and the GDMM method, are close to the value of the major strain at fracture, determined by using the spatio-temporal method.

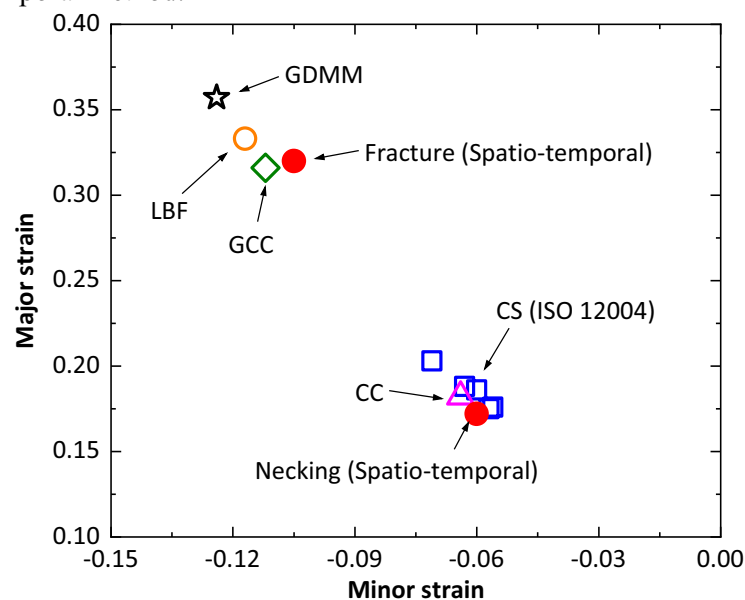


Figure 3. Comparison of the determined necking strains using the spatio-temporal method and the existing methods, CS: Cross-section method, LBF: Linear best fit method, CC: Correlation coefficient method, GCC: Gliding correlation coefficient method, GDMM: Gliding difference of mean to median method.

3. Cruciform specimen design

3.1. Geometry of cruciform specimen

To enable formability evaluation by using the biaxial testing method, two fundamental objectives must be achieved in designing cruciform specimen, i.e., 1) to initiate necking/fracture in gauge region, and 2) to achieve linear strain path with a designated strain ratio β , e.g. $\beta = 1$ for equi-biaxial tension. It has been known that compared to the uniaxial and plane-strain tensions, these two objectives are extremely difficult to realise in equi-biaxial tension. A type of cruciform specimen has been proposed to overcome this difficulty [11]. Figure 4 shows the geometry and dimensions of the proposed cruciform specimen, which includes features of notches between arms, slits in each arm, a circular thickness-reduced zone and importantly, a central thickness-reduced zone with arc-shaped profile through thickness. Except the dimensions of the thickness-reduced zones, other dimensions have been optimised to generate a relatively uniform strain distribution in the central region of the specimen [11].

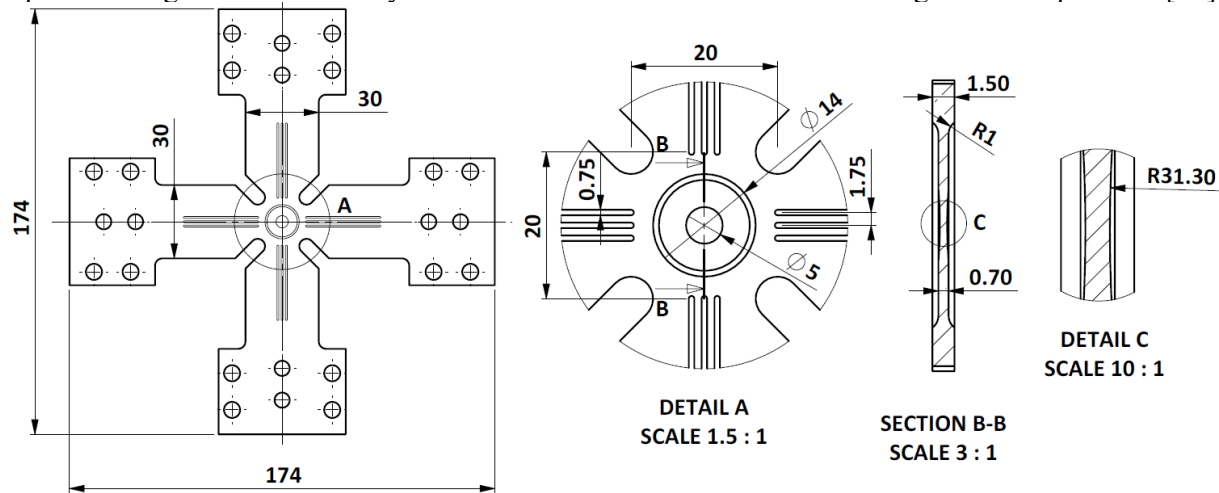


Figure 4. Geometry and dimensions (in millimetres) of cruciform specimen for formability evaluation.

3.2. Deformation under equi-biaxial tension

The AA5754 cruciform specimens were deformed under the equi-biaxial tension, by using a patented biaxial tensile system [13]. The relative grip speed in each arm is 15 mm/min. The DIC technique was adopted for strain measurement, with a constant frame rate of 125 fps. Figure 5 shows the measured distribution of major strain and thickness reduction in the circular thickness-reduced zone (diameter 14 mm), at different normalised times t/t_F . In the strain distribution at $t/t_F = 0.8$, deformation mainly concentrated in the central thickness-reduced zone due to smaller thickness, although it also occurred in other thickness-reduced zone. Both major strain and thickness reduction at the centre of the specimen is the highest. At $t/t_F = 1$, fracture started to initiate at the centre, and the highest major strain and thickness reduction were observed. This demonstrates that the first objective can be realised in the designed cruciform specimen under the equi-biaxial tension, i.e. localised necking/fracture initiates in the gauge region.

The strain distribution in Figure 5 was further analysed quantitatively. Figure 6(a) shows the thickness strain distribution along the path 1-1 perpendicular to the necking band, as indicated in Figure 5, at different normalised times. Indeed, the thickness reduction at the centre of the specimen is the highest throughout deformation. Figure 6(b) presents the strain path in the central area of the specimen where the localised necking initiates. Before $t/t_F = 0.9$, the strain path is almost linear, and corresponding strain ratio is calculated by $\beta = 1/k = 0.86$, where k is the slope of the fitted dashed line (red) for the experimental data using the least square method. This indicates that in the designed cruciform specimen under equi-biaxial tension, linear strain path with strain ratio β , which is very close to $\beta = 1$, can be achieved at the location where localised necking initiates. Therefore, the proposed cruciform specimen is able to realise the two objectives simultaneously, thus having high potential to be used for formability evaluation with the biaxial testing method. It should be noted that

the strain path abruptly changed at a time after $t/t_F = 0.9$. This is due to the increment of minor strain became zero and this phenomenon has also been observed in [14].

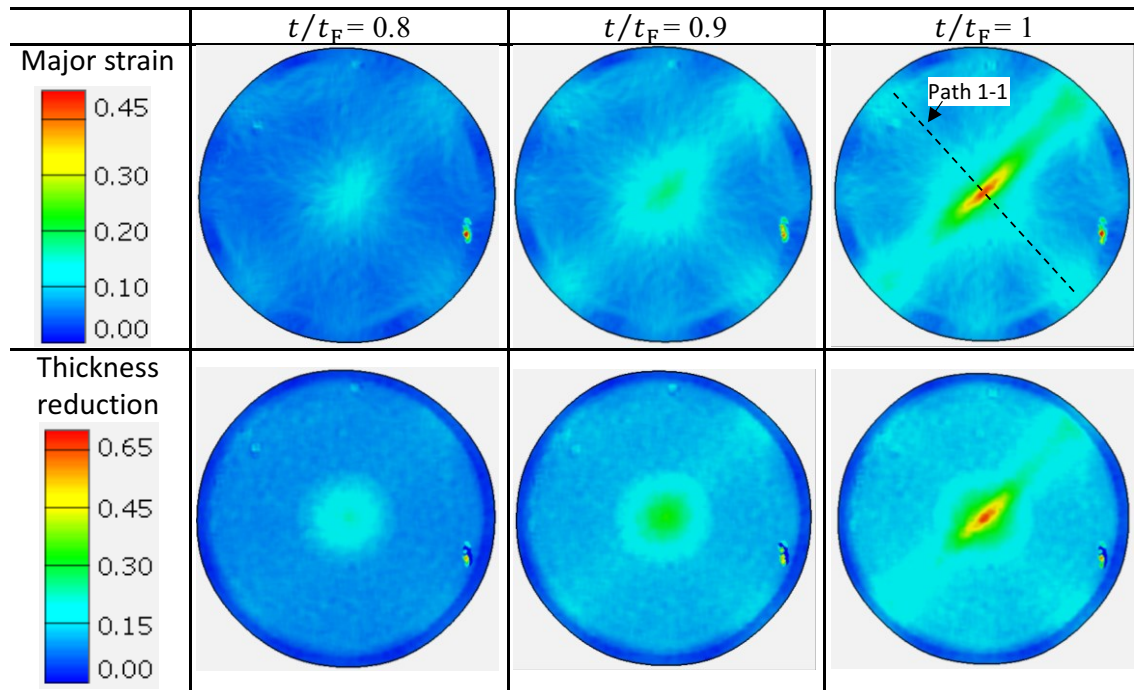


Figure 5. Strain distribution in the circular thickness-reduced zone in the cruciform specimen under equi-biaxial tension.

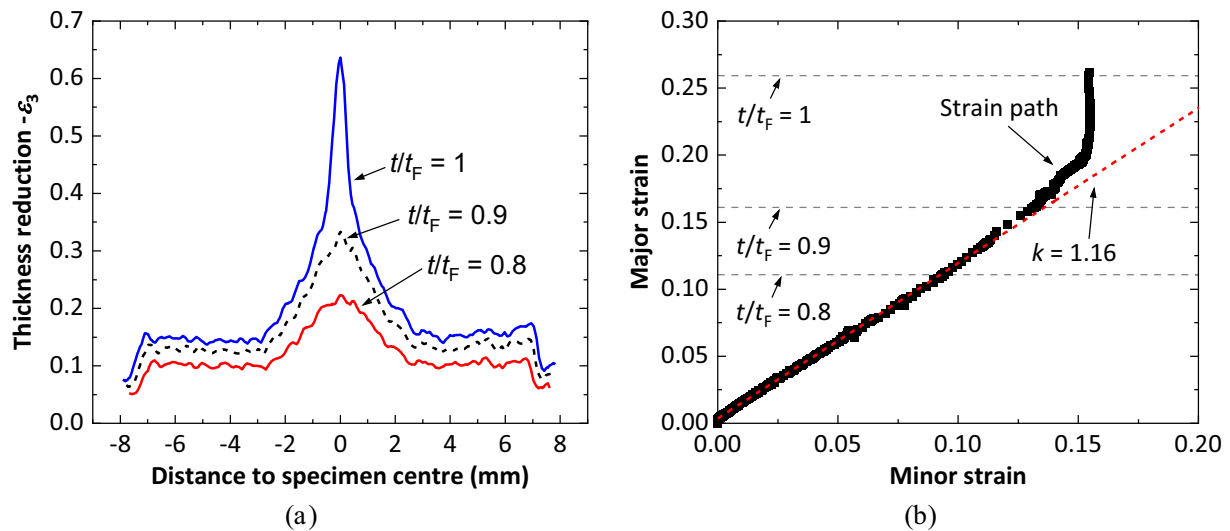


Figure 6. Strain distribution along the path 1-1 and strain path at the location where necking initiates. Note that the path 1-1 is noted in Figure 5, (a) thickness strain distribution, (b) strain path at necking.

The spatio-temporal method was applied to the biaxial tensile test for the determination of the necking and fracture strains. Figure 7(a) shows the determined onset of localised necking and fracture in the space of thickness strain within the zones BZ and RZ, by adopting the following parameter: $a = 2$, $b = 2$, $c = 2$, $d = 0.4$, and $e = 0.99$. Indeed, the thickness strain within the zones BZ and RZ has two linear relationships for the starting and final stages, and the two fitted lines, using the least square method, are able to accurately express these linear relationships. Based on the determined onset of necking and fracture, the corresponding limit strain was further determined, as shown in Figure 7(b).

The limit strain at onset of localised necking is (0.133, 0.164), and the limit strain at fracture is (0.154, 0.262).

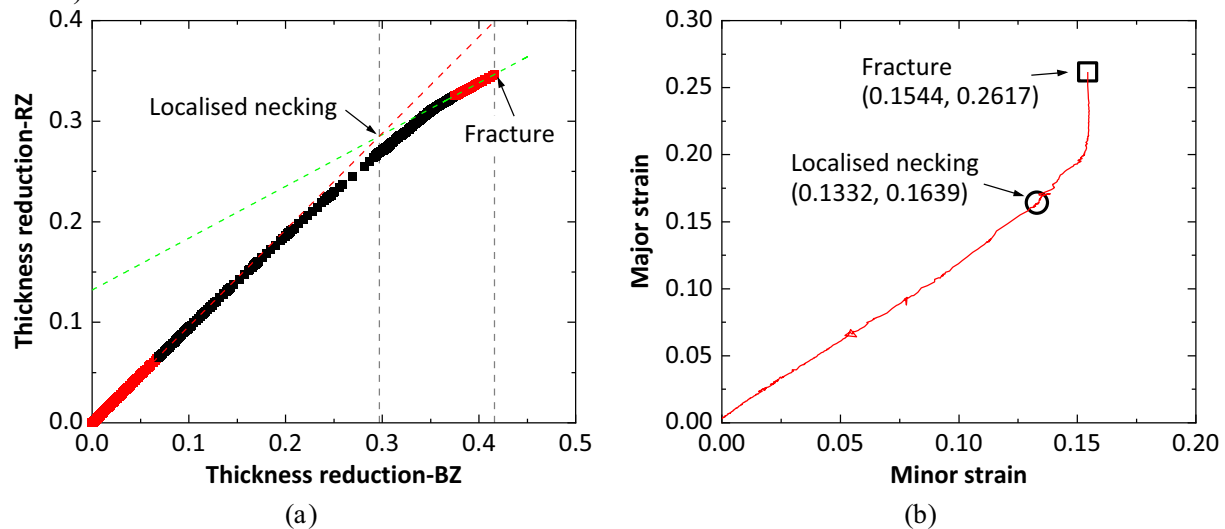


Figure 7. Determination of the onset of localised necking and fracture, and the corresponding limit strains, (a) onset of localised necking and fracture, (b) determined necking and fracture strains.

4. Conclusions

- 1) Compared with the existing methods, the novel spatio-temporal method has greater simplicity, stability and accuracy for the determination of localised necking strain.
- 2) The necking strain determined by the spatio-temporal method is almost the same as that by using the cross-section method in the standard ISO 12004-2:2008.
- 3) The designed cruciform specimen enables to initiate localised necking in the gauge region, and to achieve linear strain path with strain ratio β which is very close to 1 under the equi-biaxial tension.

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