Effect of cruciform specimen design on strain paths and fracture location in equi-biaxial tension

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Abstract
Hot stamping technologies require new methods for evaluating formability of sheet metal under various forming conditions. Biaxial tensile testing method using a cruciform specimen has been used for the applications, but a suitable cruciform specimen design has not yet been accepted. One of the challenges in designing a specimen for formability tests is to ensure proportional equi-biaxial strain paths arise at the location of fracture initiation. In this study, after reviewing existing cruciform specimen designs, three different geometries of cruciform specimen, named Type I, Type II and Type III, were proposed. Using numerical analysis and practical experiments, fracture initiation locations and corresponding strain paths in the specimens were investigated under equi-biaxial tension. Numerical simulations were performed to optimise the dimensions of Type I specimen to achieve a relatively high strain level near the centre point of the specimen. Based on the optimised dimensions, equi-biaxial tensile tests were carried out on cruciform specimens with different geometries, and strain paths at the fracture initiation locations were compared and analysed. It was found that in all cruciform specimens, equi-biaxial strain state appears only near the centre point. In the Type I and Type II specimens, fracture never initiates near the centre point, but at a location in the fillet transition zone where major strain is higher than that at the centre point. The Type III specimens have the ability to initiate fracture near the centre point, and to produce proportional strain paths with strain ratio $\beta$ close to 1 in equi-biaxial tension, 0 in plane-strain tension, and -0.5 in uniaxial tension at the locations of fracture initiation. The research provides a cruciform specimen design, Type III, which has high potential to be used for evaluating formability for sheet metal.

Keywords: Fracture; Cruciform specimen; Formability; Biaxial tensile test; Strain path; Equi-biaxial tension
1. Introduction

Hot stamping technologies, such as hot stamping of boron steel (Merklein et al., 2016) and hot form and quench (HFQ®) of aluminium alloys (Lin et al., 2008), have been developed and successfully applied in sheet metal forming processes, for producing high strength complex-shaped lightweight engineering panel components for a wide range of applications (Karbasian and Tekkaya, 2010). Both application and optimisation of these hot stamping technologies require a profound understanding of material formability at different temperatures and strain rates (Turetta et al., 2006). Forming limit diagrams (FLDs), first introduced by Keeler (1968) in tension-tension quadrant and by Goodwin (1968) in tension-compression quadrant, are commonly used for evaluating formability of sheet metals. In an FLD, limit strains at onset of localised necking under various proportional strain paths are presented in the space of major and minor strains (Bleck et al., 1998). Conventionally, an FLD is usually constructed using results obtained from practical Nakajima or Marciniak tests, in which various strain states can be realised by changing the shape of a test-piece (BS EN ISO 12004, 2008). These methods have been well used for characterising the formability of sheet metals in cold stamping conditions (Kim et al., 2011). However, it is extremely difficult to meet the thermal history (i.e. solution heat treatment, simultaneously forming and quenching) required to simulate hot stamping conditions (Shao et al., 2017).

Biaxial tensile testing methods using cruciform specimens have high potential for enabling the determination of FLDs for sheet metals under hot stamping conditions (Shao et al., 2016). In this test, cruciform specimens are deformed under the plane stress condition, and various strain states can be realised by adjusting displacement ratios in the two arm axes of the cruciform specimens (BS ISO 16842, 2014). More importantly, complex thermal profiles under hot stamping conditions can be achieved accurately in combination with a suitable heating system, such as direct resistance heating used by Shao et al. (2016) and infrared thermography used by Cam et al. (2017).

Significant efforts have been dedicated to the development of the biaxial tensile testing method for formability evaluation (Hannon and Tiernan, 2008). Zidane et al. (2010b) developed a biaxial testing system and determined an FLD for 4 mm thick AA5086 plate using an optimised cruciform specimen. Similar tests were also carried out by Leotoing et al. (2013) for the same material. In order to apply the system to thinner sheet metals, Song et al. (2017) proposed a different design of cruciform specimen and determined an FLD for 2 mm thick DP600 sheet. Abu-Farha et al. (2009) proposed and tested several cruciform specimen designs at high temperatures to achieve a high plastic deformation in gauge area, by using a patented biaxial testing fixture (Abu-Farha and Khraisheh, 2010) which adapts to an Instron universal load frame. Güler and Efe (2018) constructed
a fracture forming limit diagram (FFLD), which is another index of formability, for aluminium alloy 6061 (AA6061) and DC-04 steel sheet by using a link type biaxial tensile testing machine, as described in (BS ISO 16842, 2014). In order to mimic the complex temperature history arising in industrial hot stamping, Shao et al. (2016) developed a novel biaxial testing system, incorporating a cruciform specimen and determined an FLD for 1.5 mm thick AA6082 sheet under the hot stamping conditions. Xiao et al. (2016) also developed a biaxial tensile testing machine and determined an FLD for 1 mm thick titanium alloy sheet at several temperatures, using different cruciform specimen designs.

However, due to several major challenges, applications of the biaxial tensile testing method for sheet formability evaluation are limited. One is the lack of a widely accepted cruciform specimen design. As mentioned above, the limit strains recorded in an FLD are usually obtained from tests performed under various proportional strain paths with strain ratio $\beta$, in the range $-0.5 < \beta < 1$. This is due to the fact that the limit strains are significantly affected by both the linearity and the strain ratio of strain paths (Schlosser et al., 2019), attributed to their influence on evolution of microstructure and texture (Gurao et al., 2011). Therefore, the biggest challenge in designing a cruciform specimen for formability evaluation is to ensure proportional strain paths are engendered in it, at the location where fracture initiates. The work described in this paper is focused on specimen design for proportional equi-biaxial strain paths at the location of fracture initiation. As yet, no publication has been found dealing with this important subject.

The main purpose of this study is to provide a feasible cruciform specimen design which is capable of producing proportional equi-biaxial strain path at the location of fracture initiation, in the specimen loaded under equi-biaxial tension. Based on a review of existing cruciform specimen designs, three different geometries of specimen were proposed, named Type I, Type II and Type III. Numerical simulations were performed to investigate the effects of Type I specimen dimensions on strain distribution in the thickness-reduced zone, and to optimise the dimensions to achieve a relatively high strain level at the centre point. Based on the optimised dimensions, equi-biaxial tensile tests were carried out on cruciform specimens with the different geometries, and strain paths at the fracture initiation locations were compared and analysed.

2. Cruciform specimen designs

2.1. Review of current status

Cruciform specimens have been widely used in order to realise various deformation states in sheet metal, such as plane-strain tension and equi-biaxial tension. Table 1 presents a review of the existing cruciform specimen designs, obtained from the literature.
Table 1 Geometries of existing cruciform specimen designs in published literature.

<table>
<thead>
<tr>
<th>No.</th>
<th>Geometry</th>
<th>Literature</th>
<th>No.</th>
<th>Geometry</th>
<th>Literature</th>
</tr>
</thead>
</table>
| 1   | ![Image](image1.png) | Müller and Pöhlandt (1996)  
Banabic et al. (2005) | 2   | ![Image](image2.png) | Zhang et al. (2014)  
Zhang et al. (2015)  
Xiao et al. (2016) |
| 3   | ![Image](image3.png) | Mönch and Galster (1963)  
Kuwabara et al. (1998)  
Nagayasu et al. (2010)  
Enatsu and Kuwabara (2011)  
Hanabusa et al. (2013)  
Yuan et al. (2018)  
Hayhurst (1973) | 4   | ![Image](image4.png) | Gozzi et al. (2005)  
Kulawinski et al. (2015) |
| 5   | ![Image](image5.png) | Ferron and Makinde (1988)  
Dawicke and Pollock (1997)  
Green et al. (2004)  
Deng et al. (2015) | 6   | ![Image](image6.png) | Trautmann et al. (1997) |
| 7   | ![Image](image7.png) | Samir et al. (2006)  
Baptista et al. (2015)  
Güler and Efe (2018) | 8   | ![Image](image8.png) | Zhang and Sakane (2007)  
Abbassi et al. (2013)  
Upadhyay et al. (2018) |
| 9   | ![Image](image9.png) | Liu et al. (2015)  
Liu et al. (2016) | 10  | ![Image](image10.png) | Yu et al. (2002)  
Erinosho et al. (2016) |
| 11  | ![Image](image11.png) | Lee and Chien (2014) | 12  | ![Image](image12.png) | Tasan et al. (2008) |
Müller and Pöhlandt (1996) optimised Geometry No. 1 for obtaining a large zone of homogeneous deformation used for determining yield loci of sheet metal. In the geometry, notches were added to corners between the arms in order to promote deformation closer to the centre area. This geometry was also used by Banabic et al. (2005) to determine the yield locus of AA6181 sheet. Geometry No. 2 has differently shaped notches and it was applied for identifying parameters in Bron and Besson yield criterion (Zhang et al., 2014), and for determining yield loci of a GH738 nickel-based superalloy at high temperatures (Xiao et al., 2016). Mönch and Galster (1963) proposed Geometry No. 3 for determining yield loci for a cold-rolled low-carbon steel. In this geometry, eight slits were added to each arm in order to reduce their lateral stiffness and thus constraint imposed on deformation of the centre area. Geometry No. 3 has been recommended in (BS ISO 16842, 2014) for measuring stress-strain relations of metal sheet under biaxial tension. Other applications of this geometry have reported to clarify plastic behaviour of a cold rolled low carbon steel sheet under biaxial tension (Kuwabara et al., 1998) and to clarify the optimum strain measurement position for minimising stress measurement error in biaxial tensile tests (Hanabusa et al., 2013). Gozzi et al. (2005) developed Geometry No. 4 by reducing the number of slits in each arm and adding a curved notch to each corner. They used specimens of this geometry to determine yield loci of sheet extra high strength steel. Similar specimen geometry was also used by Kulawinski et al. (2015) for investigating the initial yield surface of a stainless steel sheet. However, the maximum strains
attainable in the centre area in cruciform specimens with Geometry No. 1, No. 2, No. 3 or No. 4 are quite low due to premature fracture in arms, and thus the specimens with these geometries are not suitable for formability tests.

In order to localise deformation in a centre square area, Hayhurst (1973) modified Geometry No. 3 to Geometry No. 5 by reducing thickness of the centre square area from as-received 6.35 mm to 4.83 mm. Geometry No. 5 was used to characterise biaxial flow curves of AA1050 (Ferron and Makinde, 1988) and AA1145 (Green et al., 2004), and to determine constitutive model (i.e. yield surface) of 1018 steel and AA2090 (Deng et al., 2015). Trautmann et al. (1997) proposed Geometry No. 6 for observing crack propagation under different biaxial loading histories. In this geometry, thickness of the centre circular zone was reduced in order to initiate fracture within the zone. For the same purpose, Samir et al. (2006) adopted Geometry No. 7 for creep-fatigue experiments, by adding four curved notches to the arm corners and a centre circular thickness-reduced zone. This geometry was also utilised for biaxial fatigue tests (Baptista et al., 2015) and formability tests (Güler and Efe, 2018). In order to apply the basis of Geometry No. 7 to thick plates, Geometry No. 8 was developed by decreasing the thickness in the intersecting area of the arms. This geometry has been employed by Zhang and Sakane (2007) to evaluate biaxial creep-fatigue life of 304 stainless steel at high temperatures, Abbassi et al. (2013) to investigate failure process in a mild steel, and Upadhyay et al. (2018) to characterise mechanical response of 316L stainless steel during biaxial loading path changes.

Liu et al. (2015) developed Geometry No. 9 by introducing four notches to the arm corners, four slits in the arms, and a centre circular thickness-reduced zone. Using specimens with this geometry, biaxial tensile tests were carried out for identifying the hardening behaviour of a 2 mm thick AA5086 sheet, in which an equivalent strain up to 30% was reached in centre area in the specimens. Geometry No. 9 was also adopted in (Liu et al., 2016) for the identification of mechanical behaviour of a DP600 dual phase steel sheet. Yu et al. (2002) developed Geometry No. 10 for determining the limit strains of a low carbon steel sheet. In this geometry, a small cross slot along the arms was designed in the centre region to reduce load-bearing capacity and thus to localise deformation in this region. The geometry was also used by Erinosho et al. (2016) for biaxial tensile tests. Geometry No.11 was developed by Lee and Chien (2014), in which two thickness-reduced zones were designed and both zones have square shape with rounded corners. This design enables to initiate fracture in the centre region of the test piece. Tasan et al. (2008) proposed Geometry No. 12 in which the profile of thickness reduction from periphery to centre was a circular arc. It was found that with this specimen design fracture was initiated at the centre point. This form of thickness reduction, together with curved notch corners, was used in Geometry No. 13. The
geometry was applied to investigate biaxial fatigue for TA6V titanium alloy and INCO718DA nickel-based alloy (Bonnand et al., 2011) and AA1050 (Cláudio et al., 2014), to study the effect of strain path change on inter- and intragranular strains for 316L stainless steel (Van Petegem et al., 2016), and to determine FLDs for TA1 titanium alloy at high temperatures (Xiao et al., 2017).

Johnston et al. (2002) modified Geometry No. 5 to Geometry No. 14 by adding a small diameter circular centre zone with added thickness reduction. Based on Geometry No. 14, Zidane et al. (2010b) proposed Geometry No. 15 for determining an FLD for 4 mm thick AA5086 plate. In this geometry, the thickness in the smaller centre circular zone was reduced with a curved profile in order to concentrate deformation at centre point of the specimen. Geometry No. 15 was further modified to Geometry No. 16 to simplify the specimen manufacture and this geometry was utilised for determining the FLD (Leotoing et al., 2013) and the FFLD (Song et al., 2016) for 4 mm thick AA5086 plate, for investigating effects of strain path changes on formability of AA5086 (Leotoing and Guiness, 2015), and for investigating the kinematics of Portevin-Le Chatelier bands induced by equi-biaxial tensile loading (Cam et al., 2017). However, Geometry No. 16 is not suitable for thinner sheet due to the necessary of large thickness reduction in centre area. In order to determine the FFLD for 2 mm thick DP600 steel sheet, Song et al. (2017) proposed Geometry No. 17, in which the thickness in the centre circular zone was reduced only on one side with a dome profile.

Based on the above review, the significant features utilised in cruciform specimen design are summarised as: (i) filleted corners between arms, to reduce stress concentrations, (ii) notches between arms, to promote deformation closer to the centre area; (iii) slits in each arm, to reduce their lateral stiffness and constraint imposed on deformation in the centre area, (iv) a reduced thickness in a centre circular zone, to localise deformation in this zone, (v) a second reduced thickness in an additional smaller centre circular zone, to improve uniformity of the strain field in this zone, (vi) a reduced thickness with a dome profile through thickness in the centre circular zone, to concentrate deformation at the centre point, the thinnest part of the specimen.

2.2. New designs and parametric study

Based on the summarised significant features in the review, three different geometries of cruciform specimen, named Type I, Type II and Type III, are proposed, as illustrated in Fig. 1, and have been investigated in order to find a suitable design which can produce proportional equi-biaxial strain path at the location of fracture initiation. The geometry Type I (Figs. 1(a)-(b)) has a centrally located circular zone with uniformly reduced thickness, in combination with fillet corners and notches between arms each of which contain three slits. The fillet corners are used to avoid stress concentration at the locations, and the notches are to promote deformation near the centre of the test
piece. The slits help to decrease lateral stiffness of the arms and constraint to the deformation in central region. Furthermore, the thickness reduction enables to concentrate deformation in the thinner zone, and thus promotes the initiation of fracture in the zone. Based on Type I, Type II (Fig. 1(c)) was developed by decreasing the diameter of the centre circular thickness-reduced zone, and adding a thicker thickness-reduced ring zone surrounding the centre zone in the central area. The smaller centre thickness-reduced zone is used to concentrate more deformation, and also to make strain distribution in the zone more uniform, while the thickness-reduced ring zone is to decrease stiffness of the centre area. Type III (Fig. 1(d)) was developed, also based on Type I, by giving the centre thickness-reduced zone a dome profile through thickness direction. Thus, the centre point of Type III specimen has the smallest initial thickness. The thickness reduction with a dome profile enables to make the deformation near the centre of the test piece larger, and thus, to prompt the initiation of fracture near the centre. For convenience, different regions in thickness-reduced zone (TRZ) in the three types of cruciform specimen are defined, as presented in Appendix A1. In Type I, there are a centre zone (CZ) and a fillet transition zone (FTZ), as illustrated in Fig. A1(a); In Type II, there are a zone CZ, two zones FTZ and a ring zone (RZ), as illustrated in Fig. A1(b); In Type III, there are a zone CZ, a zone RZ and a zone FTZ, as illustrated in Fig. A1(c).
Fig. 1 Overall shape of cruciform specimen and three different designs of the geometry at the centre region as well as corresponding parameterised dimensions. Note that the area for DETAIL A in (b), (c) and (d) is marked in (a).

All cruciform specimens have a same length of 174 mm in each axis, and a same arm width of 30 mm, as shown in Fig. 1(a). In order to optimise other dimensions, a parametric study was carried out to investigate effects of the dimensions on strain distribution in zone TRZ. As shown in Fig. 1(b), \( R_F \) is the radius of the fillet corner and \( D_F \) is the distance between two adjacent fillet corners. \( D_{S-V}, D_{S-P}, W_S \) and \( N_S \) are parameters to describe the slits in each arm. Specifically, \( D_{S-V} \) and \( D_{S-P} \) are the distance between two opposing slit ends and distance between two adjacent slits, respectively; \( W_S \) is the slit width and \( N_S \) is the slit number in each arm; \( D_C, R_C \) and \( H_C \) are dimensions to describe the centre circular thickness-reduced zone, in which \( D_C \) and \( H_C \) are its diameter and thickness respectively, and \( R_C \) is the fillet radius of zone FTZ with zone CZ. In Type II, as shown in Fig. 1(c), \( D_C, R_C \) and \( H_C \) are also used to describe the centre circular thickness-reduced zone, while \( D_R \) and \( H_R \) are the diameter and thickness of the thickness-reduced ring zone, and \( R_R \) is the fillet radius of zone FTZ with zone RZ. In Type III, \( D_C \) is the diameter of the centre thickness-reduced zone, and \( D_R, H_R \), and \( R_R \) are dimensions of the thickness-reduced ring zone, as shown in Fig. 1(d). In addition, \( R_D \) is the radius of the dome profile.

Compared with the existing cruciform specimens in literature, as presented in Table 1, the cruciform specimens proposed in this study have the following innovations: 1) all the significant features (e.g. slit, notch, thickness-reduced zone) which are summarised from the review, are combined into the specimen geometries to prompt occurrence of fracture initiation in the thickness-reduced zone, 2) the three types of thickness reduction (e.g. uniform thickness reduction and dome profile thickness reduction) are adopted for comparison, which helps to determine a suitable specimen geometry for producing proportional equi-biaxial strain path at fracture initiation location, 3) the dimensions which are optimised from the parametric study, enable to improve strain distribution in the thickness-reduced zone, especially in the circumferential direction.

3. Methodology

3.1. Material and finite element simulation

AA5754 sheets with 1.5 mm thickness were used in this study. In order to investigate the effects of Type I specimen dimensions on strain distribution in the centre area, finite element (FE) simulations of equi-biaxial tension were carried out with ABAQUS/Standard. The basic properties of AA5754 are: density 2660 Kg\(\cdot\)m\(^{-3}\), Young’s modulus 68 GPa, and Poisson’s ratio 0.3. With respect to the plastic behaviour, both the associated normal flow rule and the von Mises yield criterion were
assumed. The measured true stress-strain curve, as presented in Appendix A2, was used as input data to describe strain hardening behaviour of the material. Considering the symmetry of both geometry and boundary conditions, only a quarter model of the cruciform specimen was built. In the FE models, each specimen was meshed by hexahedral elements, with a global size of 1 mm and a smaller size of 0.2 mm in zone TRZ, to construct a finer mesh. Boundary conditions were consistent with the experimental conditions, in which the centre point of each specimen was fixed, and the same displacement rate was imposed on each arm.

For the FE simulations, as shown in Table 2, a set of specimen dimensions was chosen as reference values. By changing each dimension in turn from its reference value, for each set of changed dimensions, shown in Table 2, strain distribution in Type I specimens was simulated and compared with that in the specimen with the reference values.

<table>
<thead>
<tr>
<th>Dimensions in different regions</th>
<th>Fillet corner</th>
<th>Slit</th>
<th>Zone TRZ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RF</td>
<td>DF</td>
<td>D5−V</td>
</tr>
<tr>
<td>Reference values</td>
<td>3</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Alternative values</td>
<td>2.5</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>18</td>
<td>18</td>
</tr>
</tbody>
</table>

3.2. Experimental programme

A novel biaxial testing system, described in (Shao et al., 2016), was used to test cruciform specimens of AA5754 under equi-biaxial tension, as shown in Fig. 2(a). The biaxial testing system comprises a patented planar biaxial tensile rig (Lin et al., 2018), as shown in Fig. 2(b), which is capable of converting an input uniaxial force into output biaxial forces for deforming specimens. All cruciform specimens were deformed at a constant grip speed of 15 mm/min along the axis of each arm. The digital image correlation (DIC) technique was utilised for strain field measurement, in which deformation images were captured by using a high-speed camera at a constant rate of 125 frames per second (fps). Subsequently, all images were processed by the commercial software ARAMIS (GOM, Germany), setting up the facet size of 19 pixels and the point distance of 5 pixels.
Fig. 2 Novel biaxial testing system for stretching cruciform specimens of AA5754 under equi-biaxial tension.

4. Results and discussion

4.1. Numerical analysis - Type I specimen

a) Effect of $R_F$ and $D_F$

In order to investigate the effect of fillet corner radius $R_F$ on strain distribution in Type I specimen, FE simulations were performed with different $R_F$ values, with other specimen dimensions having the reference values in Table 2. In Figs. 3(a1)-(a3) and 3(b1)-(b3), major strain ($\varepsilon_1$) and minor strain ($\varepsilon_2$) contours in the centre region respectively are presented, when the highest major strain within zone TRZ is slightly higher than 0.1 (grey zones). As shown in Fig. 3(a2), deformation is concentrated in zone CZ because of the reduced thickness, but it also occurs in other zones, such as zone ZI-1 in Fig. 3(a1) and zone ZI-2 in Fig. 3(a3). For different $R_F$ values, greater changes arise in the field of major strain than in that of minor strain, indicating $R_F$ has a significant effect on the former. It is seen that the maximum major strain (grey zones) within zone TRZ locates in zone FTZ rather than in zone CZ. Also, other grey zones where $\varepsilon_1$ is higher than 0.1, exist outside zone TRZ, such as fillet corners and ends of slits. However, $\varepsilon_2$ at the fillet corners is negative and thus the strain ratio ($\beta = d\varepsilon_2 / d\varepsilon_1 = \varepsilon_2 / \varepsilon_1$ under proportional loading) is less than zero. For example, a point at fillet corner, as marked with yellow dot in Fig. 3(a3), has $\varepsilon_1 = 0.129$ and $\varepsilon_2 = -0.052$, thus $\beta$ is -0.40, indicating that the strain state is close to uniaxial tension.
Fig. 3 Comparison of strain contours in centre region in Type I specimens with different $R_F$ values, when the highest major strain within zone TRZ is slightly higher than 0.1 (grey zones), (a1)-(a3) major strain $\varepsilon_1$ and (b1)-(b3) minor strain $\varepsilon_2$. Paths PI-1 and PI-2/PI-3 within the centre region radiate from the centre along arm direction and fillet direction respectively. Note that due to symmetry, paths PI-1 and PI-3 have the same strain distribution in zone TRZ, but the latter covers the area in fillet corner.

In order to quantify the effect of $R_F$ on strain distribution in zone TRZ, major and minor strain distributions along paths PI-1 and PI-2, as illustrated in Fig. 3(a2), are plotted in Figs. 4(a) and (b) respectively, in which distance $r$ from centre point is normalised by radius of zone TRZ ($D_C/2$). Major strain distributions along the paths are highly dependent on $R_F$. Specifically, as shown in Fig. 4(a), when $R_F = 3$ mm, $\varepsilon_1$ on the two paths increases slightly with increasing distance from the centre point until it reaches the highest value in zone FTZ, and $\varepsilon_1$ at the centre point is 4.0% lower than the highest value. When $R_F = 2.5$ mm and 3.5 mm, $\varepsilon_1$ on the paths also increases with increasing distance from the centre point and on one of the paths it also reaches the highest value in zone FTZ. However, $\varepsilon_1$ at the centre point is 14.4% and 19.0% lower than the highest value for $R_F = 2.5$ mm and 3.5 mm respectively. As shown in Fig. 4(b), minor strain distributions have the same trend for different $R_F$ values. Specifically, $\varepsilon_2$ decreases slightly with increasing distance from the centre, while it decreases rapidly to zero in zone FTZ. In addition, it is seen that at the centre, $\varepsilon_1$ is equal to $\varepsilon_2$. 
In Type I specimens, different locations in the centre region correspond to different strain states because both $\varepsilon_1$ and $\varepsilon_2$ are different at the different locations. Fig. 4(c) shows the strain ratio $\beta$ on path PI-3 (shown in Fig. 3(a2)). It can be seen that $\beta$ has a value of 1 at the centre point whereas it decreases with increasing distance, especially in zone FTZ where it reduces rapidly to zero, and eventually reaches about -0.4 at fillet corner. This indicates that in Type I specimens, the strain state at only the centre point is equi-biaxial ($\beta = 1$). Therefore, in order to produce equi-biaxial strain path at the location of fracture initiation, it is necessary for fracture to be initiated at the centre point of cruciform specimens. In addition, of the chosen $R_F$ values, $R_F = 3$ mm is the optimum one because it results in a relatively high value of $\varepsilon_1$ and $\varepsilon_2$ at the centre point, thus promoting fracture initiation there.
FE simulations were also performed to investigate the effect of fillet corner distance \( D_F \). Shown in Figs. 5(a) and (b) is the effect of \( D_F \) on major and minor strain distributions respectively, along the paths PI-1 and PI-2. It is seen in Fig. 5(a) that major strain distributions on the two paths are highly dependent on \( D_F \). For the \( D_F \) values investigated, highest major strain within zone TRZ always appears in zone FTZ. However, \( \varepsilon_1 \) at the centre point, for \( D_F = 18 \) mm and 22 mm, is less by 28.5% and 14.7% respectively, than the highest major strain on the path, compared with 4.0% for \( D_F = 20 \) mm. This indicates that the reference value \( D_F = 20 \) mm is optimum for promoting the initiation of fracture at the centre point. As shown in Fig. 5(b), \( \varepsilon_2 \) along both paths, for all \( D_F \) values, similarly has a general trend of decreasing with increasing distance from the centre point, especially in zone FTZ where there is a rapid decrease. This is similar to the results for the \( R_C \) values shown in Fig. 4(b), and the results for other dimensions. Thus, all dimensions listed in Table 2 have little effect on the trend of minor strain distribution and will not be presented in the following sections.

![Strain distribution graphs](image)

(a) Major strain distribution  
(b) Minor strain distribution

Fig. 5 Strain distribution along paths PI-1 (solid lines) and PI-2 (dashed lines) in zone TRZ, in Type I specimens with different \( D_F \) values.

b) Effect of \( D_{SV}, W_S, D_{SP} \) and \( N_S \)

Figs. 6(a)-(d) show major strain distributions along the paths PI-1 and PI-2 in Type I specimens with different values of dimensions \( D_{SV}, W_S, D_{SP} \), and slot number \( N_S \), respectively. In all cases, the highest major strain within zone TRZ occurs only in zone FTZ. Also, major strain distributions along both paths are highly dependent on \( D_{SV}, W_S \), and \( N_S \). For example, as shown in Fig. 6(a), for \( D_{SV} = 18 \) mm \( \varepsilon_1 \) at the centre point is 23.2% less than the highest major strain whereas, for \( D_{SV} = 20 \) mm it is 4.0% less. As shown in Fig. 6(c), for different \( D_{SP} \) values, a relatively small difference between the major strain distributions exists, which indicates that \( D_{SP} \) has little effect on major strain distribution. It can be seen that the reference values of \( D_{SV}, W_S \), and \( D_{SP} \) and \( N_S \) are optimum to generation of a relatively high \( \varepsilon_1 \) at the centre point, compared with the alternative
values. It is expected that a larger arm slit number than investigated here (e.g. $N_S = 4$), would contribute to increasing $\varepsilon_1$ at the centre point. However, this could weaken the arms and result in their premature fracture.

![Fig. 6 Major strain distribution along paths PI-1 (solid lines) and PI-2 (dash lines) in zone TRZ, in Type I specimens with different values of (a) $D_{S-V}$, (b) $W_S$. (c) $D_{S-P}$, (d) $N_S$.](image)

**c) Effect of $D_C$, $R_C$ and $H_C$**

Figs. 7(a)-(c) show major strain distributions along the paths PI-1 and PI-2 in Type I specimens with different values of dimensions $D_C$, $R_C$ and $H_C$, respectively. The highest major strain within zone TRZ appears only in zone FTZ, similar to the results shown in Figs. 4-6. Moreover, major strain distribution values are highly dependent on $D_C$ and $R_C$. For example, as shown in Fig. 7(a), relative to the highest value of major strain, $\varepsilon_1$ at the centre point is 4.0% less for $D_C = 14$ mm but 14.6% less for $D_C = 16$ mm. It can be seen that decreasing $D_C$ from 14 mm (reference value) to 12 mm increases $\varepsilon_1$ at the centre point by 2.5%. However, the stiffness in centre region of the
specimen is also increased and thus the centre region is too difficult to deform. Except that the curve for the reference value is not the highest in the CZ zone, values and trends in major strain distribution for different values of $R_C$, plotted in Fig. 7(b) are similar to those for the $D_C$ values plotted in Fig. 7(a). It is shown in Fig. 7(c) that changes in both values and trends in major strain distribution are affected little (less than 2% overall at the centre point) by the chosen different $H_C$ values. Overall the dimensions chosen as reference values are considered to provide the most satisfactory strain values in the centre point zone and thus specimens with these dimensions were chosen for the practical experiments.

Fig. 7 Major strain distribution along paths PI-1 (solid lines) and PI-2 (dash lines) in zone TRZ, in Type I specimens with different values of (a) $D_C$, (b) $R_C$ and (c) $H_C$. 

(a) Different $D_C$ values

(b) Different $R_C$ values

(c) Different $H_C$ values
4.2. Practical experiments

a) Type I specimens

Type I specimens, with the optimum dimensions (reference values) as listed in Table 2, were stretched, using the novel biaxial testing system under equi-biaxial tension until the first crack was observed. Figs. 8(a1)-(a3) and 8(b1)-(b3) show major strain ($\varepsilon_1$) and minor strain ($\varepsilon_2$) contours respectively, in zone TRZ at different normalised times ($t/t_F$), where $t$ is current time and $t_F$ is time at fracture. Consistent with the numerical results, deformation is mainly concentrated in zone CZ, but also occurs locally in zone FTZ, such as zone ZI-3 indicated in Fig. 8(a2). More importantly, it can be seen that fracture initiates where the major strain is highest, that is in zone FTZ rather than at the centre point, as shown in Fig. 8(a3).

![Fig. 8 Evolution of strain contours in zone TRZ in Type I specimen subject to equi-biaxial tension at indicated normalised times $t/t_F$: (a1)-(a3) major strain $\varepsilon_1$ and (b1)-(b3) minor strain $\varepsilon_2$. Centre point zone and fracture initiation zone were selected at the centre point and the location of fracture initiation respectively.](image)

In order to quantify the strain field around the fracture initiation location, major strain $\varepsilon_1$ and minor strain $\varepsilon_2$ distributions in the zone TRZ, along path PI-4 as indicated in Fig. 8(a3) which goes through the fracture location in radial direction, at different normalised times $t/t_F$ are given in Fig. 9(a). The radial distance is normalised by radius $D_C/2$. At $t/t_F = 0.6$, $\varepsilon_1$ and $\varepsilon_2$ at the centre point are almost equal, so the corresponding strain ratio $\beta$ is about 1. With increasing distance from the centre point, at this time, $\varepsilon_1$ increases slightly until it reached the highest value of 0.074 at a location in zone FTZ, while $\varepsilon_2$ continuously decreases in zone CZ and sharply decreases in zone FTZ. The results from numerical analysis shown in Figs. 4(a)-(b) are consistent with these from practical experiments. At this moment, the highest major strain is 32.8% higher than $\varepsilon_1$ at the centre point, and $\beta$ at the location with the highest major strain was about 0.42. At $t/t_F = 0.9$, the highest
major strain in zone FTZ has increased to 0.167, which is 44.0% higher than $\varepsilon_1$ at the centre point, and corresponding $\beta$ decreased to 0.32. At $t/t_F = 1.0$, the highest major strain in zone FTZ has increased to 0.528, which is about 200% higher than $\varepsilon_1$ at the centre point. This demonstrates physically that fracture initiates in zone FTZ.

Both the linearity and the strain ratio of strain paths at the location of fracture initiation and at the centre point were evaluated. In order to minimise the effect of noise, average values were used for the evaluation, by selecting a circular zone with a diameter of $2.5 \times H_C = 1.25$ mm at the location of fracture initiation and at the centre point, named fracture initiation zone and centre point zone respectively, as illustrated in Fig. 8(a3). Fig. 9(b) shows the strain paths in the two zones, in which the two dashed straight lines are fitted using the least square method on experimental data up to $t/t_F = 0.3$. $k$ is the slope of the fitted dashed lines, and thus $\beta_A = 1/k$ is the average strain ratio of the strain path during this initial time. According to the fitted straight lines, the strain path in the centre point zone is linear, and the corresponding strain ratio is $\beta_A = 0.97$, which indicates that a proportional equi-biaxial strain path is produced in the centre point zone. However, the strain path in the fracture initiation zone is nonlinear, and the strain ratio of the strain path decreases from $\beta_A = 0.40$ at the initial stages of deformation to almost zero at fracture.

(a) Major (solid lines) and minor (dashed lines) strains
(b) Strain paths and corresponding strain ratios

Fig. 9 Strain distribution along path PI-4 in zone TRZ at indicated normalised times $t/t_F$, and strain paths in centre point zone and fracture initiation zone, in Type I specimen subject to equi-biaxial tension. Note that $k$ is the slope of the fitted dashed lines; Path PI-4, centre point zone and fracture initiation zone are shown in Fig. 8(a3).

b) Type II specimens

Type II specimens were also tested using the novel biaxial testing system under equi-biaxial tension. In Type II specimens, listed in Table 3, both $D_C$ and $R_C$ were decreased to 5 and 0.5 mm respectively. Apart from the dimensions related to the thickness-reduced ring zone, all other
dimensions were the same as the optimum dimensions of Type I specimens. Figs. 10(a1)-(a3) and 10(b1)-(b3) show major strain and minor strain contours respectively, in zone TRZ at \( t/t_F = 0.6, 0.9, \) and \( 1.0 \). Deformation occurs in zone TRZ, but mainly is concentrated in the thinnest zone CZ. In addition, uniformity of strain field in zone CZ is improved, compared with that in Type I specimens. Similar to characteristics of Type I specimens, minor strain decreases sharply in zone FTZ with increasing distance from the centre point. Furthermore and most importantly, fracture initiates at a location near zone FTZ, where the highest major strain is seen, as illustrated in Fig. 10(a3).

Table 3 Dimensions (in millimetres) of Type II specimen for biaxial tensile tests. All symbols are indicated in Fig. 1.

<table>
<thead>
<tr>
<th>( R_F )</th>
<th>( D_F )</th>
<th>( D_{S-V} )</th>
<th>( W_S )</th>
<th>( D_{S-P} )</th>
<th>( N_S )</th>
<th>( D_R )</th>
<th>( R_R )</th>
<th>( H_R )</th>
<th>( D_C )</th>
<th>( R_C )</th>
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<td>20</td>
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<td>1.75</td>
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<td>14</td>
<td>1</td>
<td>0.7</td>
<td>5</td>
<td>0.5</td>
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Fig. 10 Evolution of strain contours in zone TRZ in Type II specimen subject to equi-biaxial tension at indicated normalised times \( t/t_F \): (a1)-(a3) major strain \( \varepsilon_1 \) and (b1)-(b3) minor strain \( \varepsilon_2 \).

Major strain \( \varepsilon_1 \) and minor strain \( \varepsilon_2 \) distributions in the zone TRZ, along path PII-1 (shown in Fig. 10(a3)) through the fracture location in radial direction, at \( t/t_F = 0.6, 0.9 \) and \( 1.0 \), are plotted in Figs. 11(a) and (b). The radial distance is normalised by the radius \( D_R/2 \). Similar to the strain distributions in Type I specimens at \( t/t_F = 0.6 \), \( \varepsilon_1 \) at the centre point of Type II specimen is almost equal to \( \varepsilon_2 \). With increasing distance from the centre point, in zone CZ \( \varepsilon_1 \) increases and \( \varepsilon_2 \) decreases slightly. In zone FTZ, however, \( \varepsilon_1 \) reaches its highest value of 0.077 within zone TRZ, and the corresponding \( \varepsilon_2 \) drops rapidly. This indicates that the strain ratio \( \beta \) on the path PII-1 in zone FTZ, although greater than zero, is much lower than that at the centre point (\( \beta = 1 \)). In zone RZ, \( \varepsilon_1 \) is always lower than the highest major strain. With increasing \( t/t_F \) to 0.9, both the major
strain and minor strain distributions are similar to that at \( t/t_F = 0.6 \). Specifically, with increasing distance from the centre point, \( \varepsilon_1 \) increases slightly and reaches the highest value of 0.16 in zone FTZ, while \( \varepsilon_2 \) decreases slightly in zone CZ and decreases rapidly in zone FTZ. When \( t/t_F \) reaches 1.0, the highest major strain of 0.378 within zone TRZ occurs near zone FTZ where fracture initiates, and it is 81.7\% higher than \( \varepsilon_1 \) at the centre point.

In order to evaluate strain paths at the fracture initiation point and the centre point, two circular zones with a same diameter of 1.25 mm were selected around both points, named fracture initiation zone and centre point zone respectively, as indicated in Fig. 10(a3). Fig. 11(b) shows the strain paths in the two zones, in which the dashed straight lines were fitted using the least square method on experimental data up to \( t/t_F = 0.3 \). The strain path in the centre point zone is linear, and the corresponding strain ratio is \( \beta_A = 0.89 \), indicating an almost proportional equi-biaxial strain path. However, the strain path in the fracture initiation zone is nonlinear, and the corresponding strain ratio decreases gradually with increasing deformation, from \( \beta_A = 0.63 \) at the initial stage of deformation to almost zero at fracture.

![Diagram](image)

(a) Major (solid lines) and minor (dashed lines) strains
(b) Strain paths and corresponding strain ratios

Fig. 11 Strain distribution along path PII-1 in zone TRZ at indicated normalised times \( t/t_F \), and strain paths in centre point zone and fracture initiation zone, in Type II specimen subject to equi-biaxial tension. Note that path PII-1, centre point zone and fracture initiation zone are shown in Fig. 10(a3).

c) Type III specimens

Type III specimens, with the dimensions listed in Table 4, were also tested using the novel biaxial testing system under equi-biaxial tension. Figs. 12(a1)-(a3) and 12(b1)-(b3) show major strain and minor strain contours respectively, in zone TRZ at \( t/t_F = 0.6, 0.9 \) and 1.0. Deformation in the centre area of the specimen mainly concentrates in the thinner zone CZ. Furthermore, the highest major and minor strains occur near the centre point throughout the deformation, and both strains,
especially the minor strain, decrease gradually with increasing distance from the centre point. This is different from the strain distributions in Type I and Type II specimens. Most importantly, as shown in Fig. 12(a3), fracture initiates near the centre point of the Type III specimen, where the major strain is the highest.

Table 4 Dimensions (in millimetres) of Type III specimen for biaxial tensile tests. All symbols are indicated in Fig. 1.

<table>
<thead>
<tr>
<th>$R_F$</th>
<th>$D_F$</th>
<th>$D_{S-V}$</th>
<th>$W_S$</th>
<th>$D_{S-P}$</th>
<th>$N_S$</th>
<th>$D_R$</th>
<th>$R_R$</th>
<th>$H_R$</th>
<th>$D_C$</th>
<th>$R_D$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>20</td>
<td>0.75</td>
<td>1.75</td>
<td>2</td>
<td>15</td>
<td>1</td>
<td>0.7</td>
<td>12</td>
<td>60</td>
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</tbody>
</table>

Fig. 12 Evolution of strain contours in zone TRZ in Type III specimen subject to equi-biaxial tension at indicated normalised times $t/t_F$: (a1)-(a3) major strain $\varepsilon_1$ and (b1)-(b3) minor strain $\varepsilon_2$.

Major strain $\varepsilon_1$ and minor strain $\varepsilon_2$ distributions in the zone TRZ, along path PIII-1 (Fig. 12(a3)) through the fracture location in radial direction, at $t/t_F = 0.6$, 0.9 and 1.0, are plotted in Fig. 13(a). Both $\varepsilon_1$ and $\varepsilon_2$ at the centre point are the highest at $t/t_F = 0.6$ and 0.9 and decrease gradually with increasing distance from the centre point. Because fracture initiates near the centre point where the major strain is the highest at $t/t_F = 1.0$, a circular zone with a diameter of 1.25 mm was selected there, named fracture initiation zone, as shown in Fig. 12(a3). Fig. 13(b) shows the strain path in the fracture initiation zone, in which the dashed straight line was fitted using the experimental data up to $t/t_F = 0.3$. According to the fitted straight line, the strain path is linear until the appearance of necking, and the corresponding strain ratio before the necking is $\beta_A = 0.78$, which is close to the strain ratio $\beta = 1$ of equi-biaxial stretching. This demonstrates that Type III specimens subject to equi-biaxial tension have the ability to initiate fracture near the centre and to produce proportional strain paths with strain ratio close to 1 in the fracture initiation zone.
The feasibility of Type III specimens for producing other strain conditions was investigated by stretching the specimens under plane-strain tension and uniaxial tension separately. Fig. 14 shows the contours of major strain and thickness reduction in zone TRZ at the time immediately before fracture \( t/t_F = 1 \), and the corresponding strain paths in the fracture initiation zone in plane-strain tension and uniaxial tension tests. As illustrated in Figs. 14(a) and 14(b), fracture occurs near the centre of the specimens in the two tests. Moreover, as shown in Figs. 14(c) and 14(d), the strain path in the fracture initiation zone is almost linear and the corresponding strain ratio is close to 0 (plane-strain stretching) and -0.5 (uniaxial stretching) respectively in the plane-strain tension and the uniaxial tension tests. This indicates that Type III specimens are capable of producing other strain conditions which are necessary for FLD determination.
4.3. Discussion

In Type I specimens subject to equi-biaxial tension, strain state is different at different locations, and only the strain state near the centre point is equi-biaxial, as illustrated in Fig. 4(c). This is consistent with related work by Liu et al. (2015). The influence of the lateral extension of arms on stress/strain field in the arm intersecting area of cruciform specimens can be minimised by longitudinally slitting each arm (Mönch and Galster, 1963). However, due to the design of zone TRZ in Type I specimens, uniform stress fields cannot be produced in the arm overlap area or even in zone TRZ. In order to produce proportional equi-biaxial strain path at a location where fracture initiates, it is necessary for fracture to be initiated near the centre point of specimens, as is shown in Fig. 9(b) and Fig. 11(b).

According to the numerical results, the geometric parameters of Type I specimens have different effects on strain distribution in zone TRZ of the specimens. The dimensions \(D_F\) and \(R_F\), which determine the basic size of the cruciform specimen, influence the strain distribution significantly, as shown in Figs. 4 and 5. For each \(D_F\) value, an optimal \(R_F\) value can be determined to make the strain distribution more uniform. For example, as shown in Fig. 3, for \(D_F\) value of 20 mm adopted in this study, the optimal \(R_F\) value of 3 mm was found to improve the uniformity of the strain distribution. With respect to the parameters of the slits in arms, as shown in Fig. 6(c), increasing slit number \(N_S\) is beneficial to the uniformity of the strain distribution. However, larger slit numbers make loading capacity of arms lower and may result in premature fracture in the arms. Compared with the distance \(D_{S-P}\), the parameters \(D_{S-V}\) and \(W_S\) have significant effects on the strain distribution, as shown in Figs. 6(a)-(c). The values of these parameters can be optimised to make
the strain distribution more uniform, such as the reference values listed in Table 2. However, the highest major strain within zone TRZ always appears at a location in zone FTZ rather than near the centre point, as shown in Figs. 4-7. This is due to that the zone FTZ has extremely heterogeneous deformation, as shown in Fig. 3.

In the experimental results of Type I and Type II specimens as shown in Figs. 10 and 12, fracture initiates in zone FTZ rather than near the centre point, as predicted by numerical study. As stated above, the highest major strain within zone TRZ always appears in zone FTZ. This is confirmed by the experimental data presented in Figs. 9(a) and 11(a). Moreover, the minor strain at the location with the highest major strain is much lower than that at the centre point, which indicates that the strain ratio \( \beta \), although greater than zero, is much lower than that at the centre point \( \beta = 1 \). For most sheet metals, instability readily occurs in plane-strain tension in which the corresponding strain ratio is zero (Kuroda and Tvergaard, 2000). Thus, for a given metal, the limit major strain under equi-biaxial tension is higher than that under a strain state between equi-biaxial tension and plane strain tension. This explains why fracture initiates in zone FTZ rather than near the centre point in both Type I and Type II specimens.

Different from Type I and Type II specimens, fracture initiates near the centre point of Type III specimens, as shown in Fig. 12, and a proportional strain path with a strain ratio \( \beta \) close to 1 is produced at the location where fracture initiates, as shown in Fig. 13(b). The thickness in zone CZ is reduced with a dome profile through thickness, and thus the specimen is thinnest at the centre point. This results in the highest values of both major and minor strains near the centre point of the Type III specimen throughout deformation, as shown in Fig. 13(a), and thus fracture is initiated near the centre point. It should be noted that, even at the initial stage of deformation, both major and minor strains decrease gradually with increasing distance from the centre point. Moreover, as demonstrated in Fig. 14, the Type III specimens have the ability to produce proportional strain paths in other strain conditions, with strain ratio \( \beta \) close to 0 and -0.5 in the plane-strain tension and the uniaxial tension, respectively. This indicates that Type III specimens have high potential to be used for formability evaluation.

The geometric parameters of cruciform specimens affect fracture initiation locations significantly in equi-biaxial tension. In Type I and Type II specimens in which zone CZ has a uniform thickness, dimensions could be optimised (e.g. the reference values in Table 2) to ensure the occurrence of fracture within zone TRZ. However, fracture never initiates near the centre where the strain state is equi-biaxial. This is due to that in these specimens, zone FTZ has the highest major strain throughout deformation, and thus fracture initiates in zone FTZ. In Type III specimens, zone CZ has
a dome profile through thickness direction and the thickness at the centre is the thinnest. This enables the highest major strain and the final fracture near the centre of the specimen, indicating that the thickness reduction with a dome profile is an essential condition to ensure fracture initiation near the centre under equi-biaxial tension.

It is of interest to note that, as shown in Fig. 13(b), strain ratio in fracture initiation zone at the time immediately before fracture is close to zero, indicating that corresponding strain state shifts from biaxial strain state toward plane strain state ($\frac{d\varepsilon_2}{d\varepsilon_1} \cong 0$). Similar phenomenon is also observed in the tests on Type I and Type II specimens, as shown in Fig. 9(b) and Fig. 11(b), and in the tests on K-steel (Azrin and Backofen, 1970) and on IF steel and DP steel (Tasan et al., 2009). As postulated by Marciniak and Kuczyński (1967), this shift corresponds to a change from stable deformation to a localised deformation (Burford et al., 1991). This feature has been used to determine the onset of localised necking (Burford et al., 1991). This feature has been used to determine the onset of localised necking for forming limit evaluation (Volk and Hora, 2011).

5. Conclusions

In this study, based on a review of existing cruciform specimen designs, three different geometries of cruciform specimen, named Type I, Type II and Type III, were proposed and used to investigate fracture initiation location and corresponding strain paths under equi-biaxial tension. From the results of numerical analyses and practical experiments, the following conclusions can be drawn:

1) In cruciform specimens subject to equi-biaxial tension, equi-biaxial strain state occurs only near the centre point of the specimens, and thus, in order to produce proportional equi-biaxial strain path, it is necessary for fracture to be initiated near the centre point.

2) Dimensions of Type I specimens have different effects on strain distribution in the thickness-reduced zone (TRZ), and there exists a set of dimensions which minimises the difference between the major strain at the centre point and the highest major strain within zone TRZ.

3) In Type I and Type II specimens under equi-biaxial tension, fracture never initiates near the centre point of the specimens, but at a location in the fillet transition zone (FTZ), where the major strain is higher and the corresponding strain ratio $\beta$, although greater than zero, is less than that at the centre point.

4) Type III specimens have the ability to initiate fracture near the specimen centre and to produce proportional strain paths with strain ratio $\beta$ close to 1 (equi-biaxial stretching), 0 (plane-strain stretching) and -0.5 (uniaxial stretching) at fracture initiation locations. This indicates that the specimen design has high potential to be used for formability evaluation for sheet metals.
5) Compared with the strain distributions in Type I and Type II specimens, a large gradient of major strain and minor strain can be observed around the centre of Type III specimens in radial directions, even at the initial stage of deformation.

Acknowledgements
The authors would like to thank EPSRC for financial support under the grant number EP/R001715/1 on “Lightform: Embedding Materials Engineering in Manufacturing with Light Alloys”. R. Zhang also appreciates financial support from the CSC-Imperial Scholarship (Grant no. 201700260069). HFQ® is a registered trademark of Impression Technologies Limited. Impression Technologies Limited is the sole licensee for the commercialisation of the HFQ® technology from Imperial College London.

Appendix A1

![Diagram](image)

Fig. A1 Different zones within zone TRZ in cruciform specimens with the three proposed geometries. TRZ – thickness-reduced zone; CZ – centre zone; FTZ – fillet transition zone; RZ – ring zone.

Appendix A2

Uniaxial tensile tests were carried out to measure true stress-strain curve of 1.5 mm thick AA5754 sheet at a constant speed of 10 mm/min. Dog-bone shaped specimens were cut along the rolling direction of the as-received AA5754 sheet, as shown in Fig. A2(a), and the measured true stress true strain curve was plotted in Fig. A2(b).
Fig. A2 Specimen and results from a uniaxial tensile test on 1.5 mm thick AA5754 sheet.

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