Cruciform specimen design for large plastic strain during biaxial tensile testing

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Abstract. The cruciform biaxial tensile test can be used to map the hardening evolution of the yield surface over a wide range of loading paths, which is useful for calibrating and validating the advanced material models. However, when cruciform specimens following ISO Standard 16842 are used, equivalent plastic strain in the gauge region is limited to only ~0.03 for DP590. In this study, a new method was developed to strengthen the arms of ISO Standard cruciform specimens in order to achieve greater plastic deformation in the gauge region. Arm strength of cruciform specimens was enhanced by laser deposition of thickening layers using materials compatible with the base metal. Furthermore, the slit geometry in the arms was adjusted to improve strain distribution and delay fracture. To verify the proposed method, cruciform specimens of different base materials (Cr4, DP590, DP780 and DP980) were tested in a biaxial tensile testing system with the aid of digital image correlation (DIC) techniques to characterize the strain fields within the gauge region. The laser-deposition-affected zones were negligible for the base materials according to optical microscopy. For DP590, the laser deposition method provided an increase of equivalent plastic strain in the gauge region from ~0.03 to ~0.11 for various loading paths. Consequently, evolution of an experimental yield locus was obtained at equivalent plastic strains up to ~0.11 for DP590. Continuing work with Cr4, DP780 and DP980 materials increased equivalent plastic strains to different degrees under nearly plane strain conditions (biaxial force ratio of 1:2).

1. Introduction
Finite element analysis (FEA) has been used to predict deformation behavior of sheet metal during forming processes. The accuracy of FEA is very important to eliminate costly die tryout procedures. As one of the typical material testing methods under multiaxial stresses that is indispensable for validating advanced material models describing plastic anisotropy, biaxial tensile tests utilizing cruciform specimens have several advantages including subjecting specimens under an arbitrary stress ratio and in-plane deformation without any influence of friction, through-thickness stress or bending conditions [1]. One focus of research on biaxial tensile testing in recent decades has been the design of cruciform specimen geometries. Specimens with a variable cross-section thickness have been designed and developed by many researchers in order to introduce higher plastic strain and even fracture in the thinner specimen center [2]. However, the physical process to thin the specimen in the gauge region can cause significant effects on the measured mechanical properties of the material. The ISO 16842:2014 Standard [3] was established to specify the biaxial tensile testing method using a uniform...
thickness cruciform specimen made of sheet metals. However, the obtainable plastic strains in the
gauge region of an ISO Standard specimen are limited when premature fracture occurs at one arm of
the specimen. In recent years, several innovative methods were proposed to increase plastic
deformation in the gauge region of cruciform specimens by the outside regions (i.e. arms) relative to
the gauge region. Mitukiewicz et al. [4] achieved almost 0.08 plastic strain in cruciform biaxial tensile
testing for a cold-rolled DC05 steel and the arms were reinforced by plastic deformation to get a
higher yield point. It is possible to conclude from the above literature that the achieved plastic stain in
the gauge region of cruciform specimens during biaxial tensile testing remains to be expanded
urgently for advanced high strength steels (AHSS). In this study, a slit arm strengthening method by
laser deposition of thickening layers using materials compatible with the base metal was investigated
to expand the measurable plastic strain in cruciform biaxial tests. The cruciform specimen design was
verified by four sheet metal materials including a mild steel and three advanced high strength steels.

2. Design of cruciform specimen
In order to strengthen the slit arms of the cruciform specimens, laser deposition, an additive
manufacturing method, is proposed to increase the arm thickness as illustrated in Figure 1a. The
surface of laser-deposited region on the specimen was cleaned using dust-free cloth with alcohol prior
to laser deposition. Welding wires of Cr12MoV having a diameter of ~0.3 mm were heated and melted
by laser, solidified by air and the original surface of laser-deposited region was completely covered by
several parallel arrangements of solidified welding wires. The thickness of arms was increased by ~0.5
mm after applying laser deposition on both sides of the arms. The laser power and other processing
parameters used in this process are listed in Table 1.

Table 1. Laser deposition conditions.

| Machine | Power | Rated voltage | Frequency | Pulse width | Manual feed |
|---------|-------|---------------|-----------|-------------|-------------|
| TFL-200III 6 kW | 380 V ± 5% | 1.4 Hz | 9.0 ms | About 80 mm/min |

The dimensions of a cruciform specimen based on ISO Standard are illustrated in Figure 1b with a
gauge region (45 mm by 45 mm square) enclosed by the four slit arms. Seven slits with a width of
~0.2 mm, with a length of ~50 mm were arranged on each of the four arms in order to produce a
uniform stress distribution in the gauge region. The outer profile, slits and gripper holes of the
cruciform specimens were cut by laser. Laser deposition was applied on the surface of the cruciform
slit arms after the laser cutting of specimens. The gauge region (a 45 mm by 45 mm square) and the
laser-deposited region with a width of 45 mm and with a length of ~60 mm are shown in Figure 1c.

Figure 1. (a) Illustration of laser deposition process; (b) Dimensions of cruciform specimen based on
ISO Standard, (c) the gauge region and laser-deposited region in the laser-deposited specimen.

Usually, several fixed ratios of biaxial forces \(F_x:F_y\), for example, 0:1, 1:4, 1:2, 3:4, 1:1, 4:3, 2:1,
4:1 and 1:0 were chosen to obtain yield information in the first quadrant of stress space during
proportional deformation. In this study, the data associated with force ratios of 0:1 and 1:0 were
obtained from standard uniaxial tensile tests of specimens along 0° and 90° to the rolling direction
(RD), while the data associated with the other seven biaxial force ratios were obtained from biaxial
tensile tests of cruciform specimens. Specimens were positioned in the testing system with RD and TD
along the X-axis and Y-axis, respectively. Nomenclature of cruciform specimens is shown in Table 2.
When laser deposition was applied on arms of the cruciform specimens to obtain larger plastic strain
in the gauge region, the slit geometry in the arms of ISO Standard cruciform specimens was adjusted
to improve strain distribution and delay fracture. Slit geometries for the seven biaxial force ratio
specimens are shown in Table 3. Laser deposition was only applied on two arms in X direction for X4y1 and X2y1 specimens and only on two arms in Y direction for x1Y2 and x1Y4 specimens. Laser deposition was used on all four arms in both X and Y directions for X4Y3, X1Y1 and X3Y4 specimens.

**Table 2.** Nomenclature of cruciform specimens.

| Cruciform specimens | Biaxial force ratio | Laser-deposited arms |
|---------------------|---------------------|----------------------|
| YmYn                | F_x:F_y = m:n        | No laser deposition (ISO Standard) |
| XmYn                |                      | Two arms in X direction |
| XmYn                |                      | Two arms in Y direction |
| XmYn                |                      | Four arms in both X and Y directions |

**Table 3.** Geometry of slit arms in the cruciform specimen with laser deposition.

| Number and width of slits at X arms | 7 × 0.2 mm | 5 × 0.7 mm | 5 × 2 mm |
|-------------------------------------|------------|------------|---------|
| Number and width of slits at Y arms | 5 × 2 mm | 5 × 0.7 mm | 7 × 0.2 mm |

**3. Experimental details**

In this study, a mild steel sheet (Cr4) and three dual phase steel sheets (DP590, DP780 and DP980) were used to verify the proposed method. Thicknesses and mechanical properties including yield strength (YS), tensile strength (TS), total elongation (TE) and r-values obtained from uniaxial tensile tests along RD are listed in Table 4.

**Table 4.** Mechanical properties of steel sheet metals used in this study.

| Materials | Thickness [mm] | YS [MPa] | TS [MPa] | TE [%] | r-value |
|-----------|----------------|----------|----------|--------|---------|
| Cr4       | 0.6            | 145      | 285      | 52.3   | 2.03    |
| DP590     | 1.5            | 355      | 630      | 25.3   | 1.03    |
| DP780     | 1.6            | 547      | 873      | 20.2   | 0.64    |
| DP980     | 1.2            | 701      | 1013     | 12.4   | 0.82    |

Uniaxial tensile specimens following ASTM Standard along RD with and without laser deposition on the gauge region were tested with a crosshead speed of 10 mm/min at room temperature to evaluate the increase of load-carrying capacity attributed to laser deposition. Biaxial tensile tests of cruciform specimens were conducted on a biaxial testing system MTS BIA5105 [5] at room temperature. Force control mode was used to ensure continuous proportional loading during testing. To verify the laser deposition method, biaxial tensile tests under seven ratios of biaxial forces: 1:4, 1:2, 3:4, 1:1, 4:3, 2:1, and 4:1 with ISO Standard cruciform geometry as well as the laser-deposited cruciform specimens were conducted for DP590. For the sheet materials Cr4, DP780 and DP980, ISO Standard cruciform specimens (x1y2 specimens) and the laser-deposited cruciform specimens (x1Y2 specimens) were tested under the biaxial force ratio of 1:2, where the gauge region of cruciform specimens was stretched following a nearly plane strain path. Digital image correlation (DIC) techniques were applied to measure strain in both uniaxial and biaxial tensile tests. In order to investigate the sizes of laser-deposition-affected zones on the steel specimens, optical microscopic observation at cross section of laser deposition boundary was performed via optical microscopy for Cr4, DP590, DP780 and DP980.

**4. Results and discussion**

4.1. Laser-deposition-affected zones (LDAZs)

Photomicrographs of A and B regions at cross section A-A of laser-deposited cruciform specimens for DP590 are shown in Figure 2, in which the laser deposition layer (Cr12MoV), LDAZs and base
material are clearly distinguished. Figure 3 presents the Vickers hardness distribution along the thickness direction at the laser-deposited region of DP590. The DP590 material had an average Vickers hardness of ~210 HV, while the laser deposition layer (Cr12MoV) ranged from 250 HV to 380 HV. Vickers hardness distribution transitioned at LDAZs from the base material to the laser deposition layer (Cr12MoV). Two dimensions \( W_{\text{LDAZ}} \) and \( t_{\text{LDAZ}} \) were defined to evaluate the width of LDAZ at the boundary of the laser-deposited region and the thickness of LDAZ. The measured \( W_{\text{LDAZ}} \) and \( t_{\text{LDAZ}} \) based on photomicrographs of cross sections of Cr4, DP590, DP780 and DP980 are listed in Table 5. Note that the maximum \( W_{\text{LDAZ}} \) and \( t_{\text{LDAZ}} \) among the investigated steels were ~0.27 mm and ~0.21 mm, respectively, which is negligible compared to the size of the gauge region of the cruciform specimens. Hence, LDAZs were limited and their effect on mechanical properties within the gauge region material were ignored.

![Figure 2](image.png)  
**Figure 2.** Photomicrographs of A and B regions of DP590 laser-deposited cruciform specimens.  

![Figure 3](image.png)  
**Figure 3.** Through-thickness variation of Vickers hardness.

| Materials | Cr4 | DP590 | DP780 | DP980 |
|-----------|-----|-------|-------|-------|
| \( W_{\text{LDAZ}} \) [mm] | 0.04 | 0.20  | 0.21  | 0.27  |
| \( t_{\text{LDAZ}} \) [mm] | 0.09 | 0.12  | 0.18  | 0.21  |

4.2. Increase of load-carrying capacity by laser deposition

It is important to ensure that the percentage of load-carrying capacity increase was high enough to prevent the fracture at the arms of cruciform specimens during biaxial tensile testing. The load-displacement curves of uniaxial tensile tests using the original specimens and laser-deposited specimens along RD for each material, Cr4, DP590, DP780 and DP980, are shown in Figure 4. The maximum load was increased by ~103\% for Cr4, ~34\% for DP590, ~19\% for DP780 and ~30\% for DP980 because of the thickness increase by laser deposition method.

![Figure 4](image.png)  
**Figure 4.** The load-displacement curves of uniaxial tensile tests using the original specimens and laser-deposited specimens along RD: (a) Cr4, (b) DP590, (c) DP780 and (d) DP980.

4.3. Results of cruciform biaxial tensile tests

Fracture location is of utmost importance for biaxial tensile testing. All of the ISO Standard cruciform specimens (without laser deposition) fractured at one of the slit arms as shown in Figure 5a. None of the x1Y2 specimens fractured at the slit arms for all materials, Cr4, DP590, DP780 and DP980, and the failure modes are shown in Figure 5b-e. Figure 5b presents failure at the gripper holes for x1Y2 specimens of Cr4 marked by the red arrows because of the low strength of the Cr4 material. For the x1Y2 specimens of DP590, DP780 and DP980, two cracks initiated at the inner slit ends on the x-arms due to the localized stress concentrations, and the cracks rapidly propagated along the X direction into
the gauge region of the specimens. The gauge region was ripped completely and presented a polyline as shown in Figure 5c or a straight line in Figure 5d and 5e. It can be concluded that the laser deposition method is effective to strengthen the slit arms of cruciform specimens to prevent arms failure for all tested materials. Hence, future work will include developments to strengthening the slit end locations or to otherwise reduce stress concentrations in order to further increase uniform plastic deformation within the gauge region.

**Figure 5.** (a) Fractures on one slit arm of ISO Standard cruciform specimens; Failure modes of x1Y2 specimens for (b) Cr4, (c) DP590, (d) DP780 and (e) DP980.

True stress and plastic strain components in the deformed gauge region of the tested cruciform specimens were calculated accurately based on the load data and DIC data under the assumption of the Hooke’s law and the volume constancy in plastic deformation according to the procedure proposed by Min et al. [5]. The von Mises stresses and equivalent plastic strains were derived from the true stress and plastic strain components for all the biaxial tensile specimens. Figure 6 presents von Mises stress vs. equivalent plastic strain curves of x1y2 specimens and x1Y2 specimens for Cr4, DP590, DP780 and DP980. The maximum equivalent plastic strain ($\varepsilon_{\text{Pmax}}$) on the hardening curves obtained from x1y2 specimens (ISO Standard) were limited to ~0.03 for Cr4, DP590 and DP780 and less than 0.01 for DP980 due to premature fracture occurring on one y-arm of the specimen. Hardening curves calculated from x1Y2 specimens (with laser deposition) followed the curves from ISO Standard specimens very well at the period of small equivalent plastic strain for all the tested materials. And $\varepsilon_{\text{Pmax}}$ under the force ratio of 1:2 was increased by laser deposition for all tested materials, from 0.031 to 0.110 for Cr4 and DP590, from 0.029 to 0.083 for DP780 and from 0.009 to 0.052 for DP980, which is of significance to the experimental measurement of not only work hardening behavior under biaxial tension but also yield loci at large plastic strains of sheet materials. The laser deposition method was verified by the four investigated steel sheets for achieving much larger plastic strains in the gauge regions of the cruciform specimens loaded at the force ratio of 1:2.

**Figure 6.** Von Mises stress vs. equivalent plastic strain curves from x1y2 specimens (ISO Standard) and x1Y2 specimens (with laser deposition): (a) Cr4, (b) DP590, (c) DP780 and (d) DP980.

The concept of plastic work contour was adopted to investigate the yield behavior of sheet materials. Figure 7a compares the experimental yield loci of DP590 from xymn specimens (ISO Standard) and Xymn (4:1 and 2:1), xymYn (1:2 and 1:4), XymYn (4:3, 1:1 and 3:4) specimens associated with four corresponding plastic strains ($\varepsilon_{\text{Pmax}}$) along RD of 0.002, 0.01, 0.02 and 0.03. $\varepsilon_{\text{Pmax}}$ under the biaxial force ratios of 1:4, 1:2, 3:4, 1:1, 4:3, 2:1, and 4:1 for DP590 was approximately 0.03 using xymn specimens (ISO Standard) due to premature fracture on one arm of each specimens. To quantitatively evaluate the difference in the experimental yield loci obtained from ISO Standard specimens and laser-deposited cruciform specimens, a relative difference was proposed and illustrated in Figure 7b. The relative difference is actually the ratio of the “distance” between the yield stress data pair from ISO Standard and laser-deposited specimens to the “distance” between the yield stress data pair from ISO Standard cruciform specimens and the origin in the yield locus diagram. The maximum value of the relative difference was ~3.55% among all the conditions, which is small enough to
demonstrate the accuracy and feasibility of the proposed cruciform specimen design with laser deposition method. Experimental yield loci at larger $\varepsilon_P^0$ along RD up to $\sim0.11$ was obtained by the biaxial tensile tests using laser-deposited cruciform specimens as shown in Figure 7c. Yield stress pairs beyond the dashed plastic work contour line can only be measured using laser-deposited cruciform specimens.

![Figure 7](image)

**Figure 7.** (a) Comparison of experimental yield loci of DP590 obtained from ISO Standard and laser-deposited cruciform specimens; (b) Illustration of the relative difference to evaluate the difference in the experimental yield loci obtained from ISO Standard and laser-deposited specimens; (c) Experimental yield loci at larger $\varepsilon_P^0$ obtained from laser-deposited specimens of DP590.

**Conclusions**

The use of laser deposition techniques to thicken and thereby strengthen the slit arms of cruciform specimens based on ISO Standard was investigated to expand the measurable strain range in the biaxial cruciform tests for Cr4, DP590, DP780 and DP980. The laser-deposition-affected zones caused by laser processing were limited according to optical microscopy and their effect on mechanical properties within the gauge area material can be ignored. The measurable plastic strain range in the gauge region was increased using the newly designed cruciform specimens with the laser deposition method on the slit arms of cruciform specimens compared with ISO Standard cruciform specimens for Cr4, DP590, DP780 and DP980. Premature fracture occurring on one arm of cruciform specimen during biaxial tensile testing was prevented by strengthening the slit arms. The accuracy and feasibility of the proposed cruciform specimen design with the laser deposition method has been validated by the comparison between the yield loci obtained from both specimen types. For DP590, yield loci with equivalent plastic strains up to $\sim0.11$ were experimentally measured using the laser-deposited cruciform specimens, compared to $\sim0.03$ using the ISO Standard.

**References**

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**Acknowledgements**

Yong Hou, Junying Min and Jianping Lin would like to acknowledge the financial support for this research provided through GM collaborative research (GAC2214).