Materials Research Proceedings 28 (2023) 1463-1470 https://doi.org/10.21741/9781644902479-158

Suitability evaluation of pre-formed cruciform sample without thickness reduction for high strain values in the center of the specimen under different strains paths

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Keywords: Cruciform Sample, Biaxial Tensile Test Simulation, Ductile Damage Criterion

Abstract. In this study, the Finite Element (FE) simulation of an initially pre-deformed DC-5 steel cruciform specimen has been carried out and compared to experimental results. A new geometry of the sample with local reinforcements and without thickness reduction allows distribution of plastic deformation and gets high strains in its gauge region. The simulation is divided into two steps. The first one introduces initial deformation to the sample arms. For the second step, the calculated strain field is introduced as an initial pre-strain field before the application of loading along the two perpendicular arms of the cruciform specimen during the in-plane biaxial tensile test. The described numerical study expands the knowledge of material plastic flow using a ductile damage criterion under different biaxial tensile strain paths. The numerical and experimental results are in good agreement for different strain paths, from uniaxial to equibiaxial strain states.

Introduction

Sheet metal forming is a very popular manufacturing process in many industrial sectors. Therefore, the knowledge of the mechanical behaviour of materials under large plastic strain is essential to build reliable numerical models for the prediction of the final shape and quality of formed parts. The characterization of mechanical behaviour needs dedicated tests, able to reproduce the forming conditions of the processes. Different tests have been proposed to characterize anisotropy, flow stress, or forming limits (at necking or at rupture). Some of them are very common and standardized, like the Nakazima [1] or Marciniak [2] tests for the determination of Forming Limit Curves (FLC). Non-conventional tests have been also proposed to improve the knowledge of the material under complex loadings, including multiaxiality or non-linear strain paths for high strains. The use of cruciform shapes [3] stretched along two perpendicular directions in the sheet plane is very promising. Unfortunately, the level of strain reached in the gauge region is generally low and not suitable for the forming applications. Many cruciform shapes have been proposed and optimized to achieve a localization of high strains at the centre of the samples, before necking and rupture onset in the arms.

In order to localize the strains at the centre of the samples, a reduction of sheet thickness is proposed in the gauge region. Besides, longitudinal slots are generally designed to decrease the transversal stiffness of the arms [4]. The number and the position of each slot can have a great influence on the strain and stress fields in the central zone of the samples. Recently, Zhang et al. [5] conducted an extensive review of the existing cruciform specimen designs. The authors proposed three different geometries of samples which subsequently were evaluated numerically and by experiments.

The reduction of sheet thickness can affect the characterization of the mechanical behaviour. Some defects may occur when reducing the thickness (surface finish, precision for small thicknesses) and the behaviour of the material is not always homogeneous through the sheet thickness. In order to avoid this operation, a new cruciform shape with a constant thickness in the gauge region was proposed [6]. Out of plane deformations were applied around the gauge region to strengthen the connection zone between the arms and the central region.

The aim of this study is to evaluate the potential of this new specimen to achieve large strains in the gauge region for different strain paths. A Finite Element (FE) model of the pre-forming step followed by the in-plane biaxial stretching of the specimen is defined. A comparison is done between the predictive strain fields and the experimental ones from the Digital Image Correlation (DIC) method.

Cruciform Sample

Sample shape. The sample has been designed (arms' length and dimensions of the middle part) according to the capacity of the biaxial testing machine [7]. The geometry is in accordance with the international standard ISO 16842 [8] which recommends that the ratio between the sample thickness "a" and its arm width "B" should be smaller than 0.08 (Fig.1). The width of the arms is B = 30mm and the thickness of the sample is a = 0.5mm.

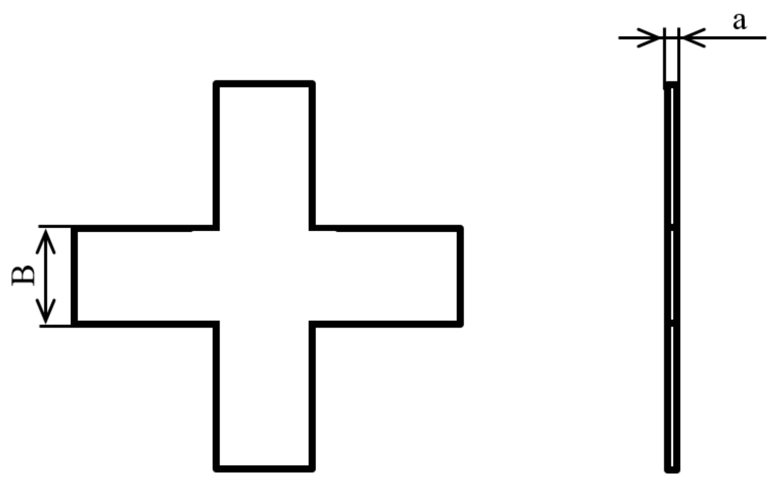

Fig. 1. Sheet thickness "a" and the arm width "B".

In order to achieve higher plastic deformation in the gauge region during biaxial stretching, the sample is preformed (Figs. 2 and 3). The aim of this preforming operation is to strengthen the sample material in the junction area between the arms and the gauge region. This solution has been already described in the previous work of Mitukiewicz and Głogowski [6].

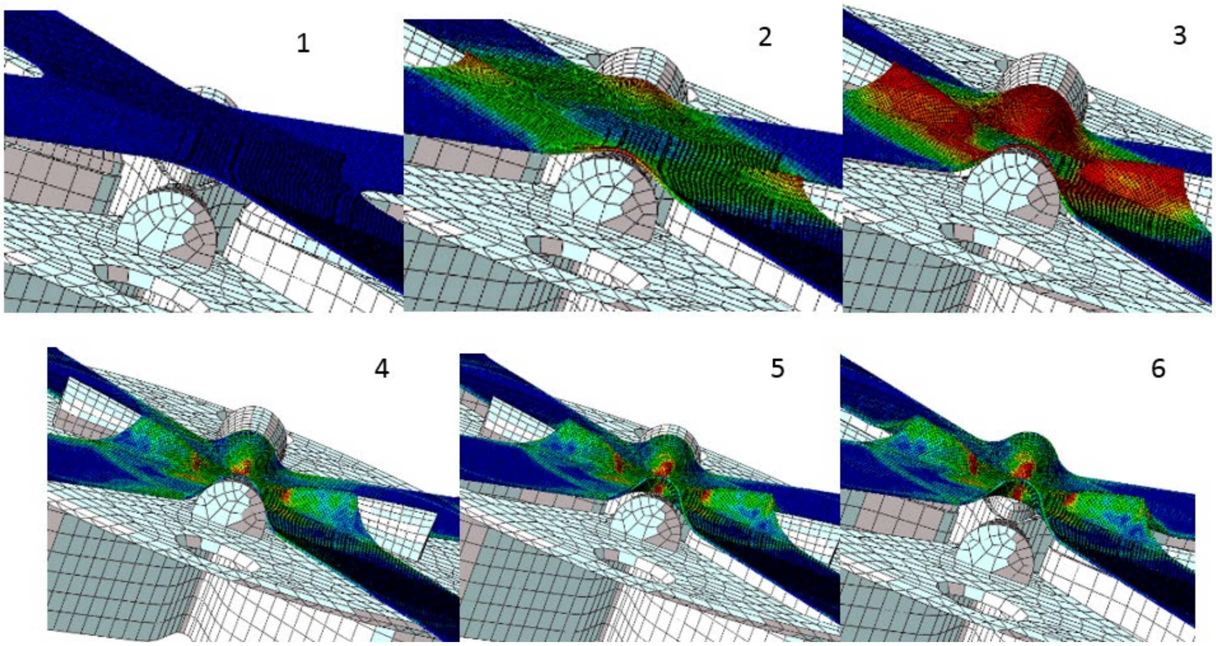

Fig. 2. Cruciform sample preforming (1 to 6 - successive steps).

Material. For this study, a DC-5 low-carbon steel specimen is used. The elastic mechanical properties of this material are as follows: Young's modulus of 210 GPa and Poisson's ratio of 0.3. Regarding the plastic behavior, an isotropic plastic criterion of von Mises is assumed with an initial yield stress of 225 MPa. The plastic strain hardening behavior is described by means of the true stress versus equivalent plastic strain curve from a uniaxial tensile test performed along the rolling direction (Fig. 3).

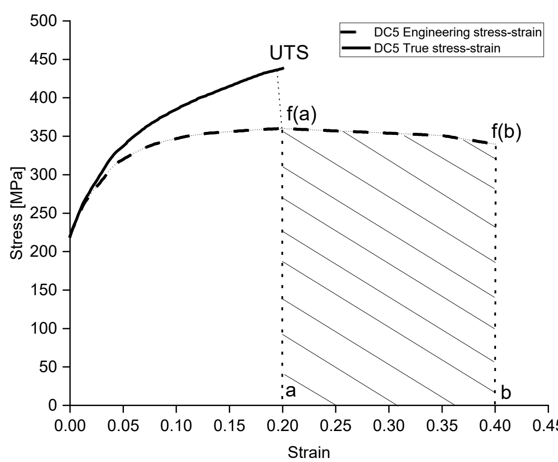

Fig. 3. True stress-plastic strain curve vs. engineering stress-plastic strain curve (UTS - ultimate tensile strength).

In-Plane Biaxial Test

Experimental setup. To test the samples, a servo-hydraulic testing machine provided with four independent dynamic actuators is used (Fig. 4). Thanks to an efficient servo-hydraulic control, the center point of the sample is always maintained stationary during the tests. The loading capacity of the machine is 50KN for each actuator and a wide range of testing velocities can be applied (from quasi-static to 2m/s).

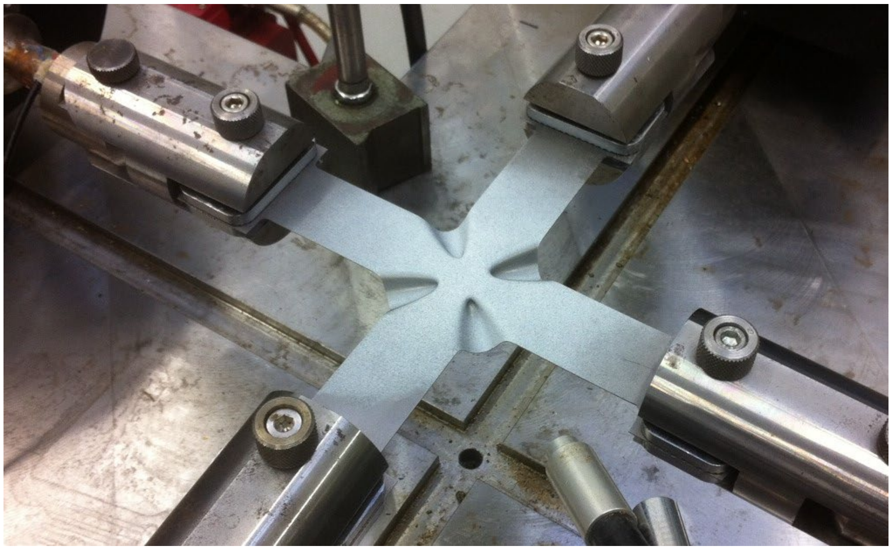

Fig. 4. Experimental setup with the pre-deformed cruciform sample.

During the test, the gauge region of the cruciform sample is filmed. The image resolution is 1024pixels×1024pixels and the acquisition rate is 250 frames/s. A random speckle pattern is applied on the surface of the specimen (Fig. 5). For the calculation of the strain field at the top surface of the specimen, the DIC method is used thanks to the CORRELATE software of the GOM Company.

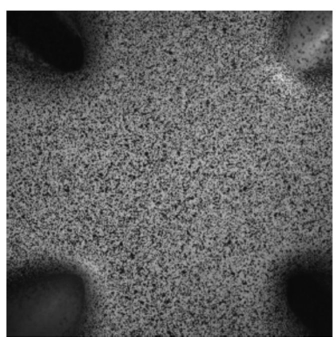

Fig. 5. Random speckle pattern applied on the top surface of the gauge region.

Loading conditions. The strain path measured at the center of the sample is directly linked to the ratio of actuator velocities applied along the two perpendicular directions of the biaxial test. By changing the velocity ratio, all the strain states between uniaxial and equibiaxial stretching can be reached.

Three loading conditions were studied:

- Biaxial stretching (**case 1**): the same velocity ($V=V_X=V_Y=1$mm/s) is applied along the two perpendicular directions
- Near plane strain (**case 2**): the velocity of $V_X=1$mm/s is applied along the rolling direction and a smaller velocity ($V_Y=0.02$mm/s) is applied along the perpendicular direction to compensate the Poisson effect.

- Uniaxial stretching (**case 3**): only the velocity (V_X =1mm/s) along the rolling direction is applied. No velocity is applied along the perpendicular direction, the sample remains free.

FE Model

The finite element modeling is performed using Abaqus software. To simulate the in-plane biaxial tensile test of this reinforced sample, two steps are defined in the FE model: the punching process (Step-I) and the tensile test process (Step-II). A view of the components of the punching die and the 3D model assembly are shown in Fig. 6. The model consists of three parts, the upper part, the cross holder, and the base part. A cruciform sample is placed between the bottom base and the cross holder to prevent any movement of the specimen during the forming process (Step 1).

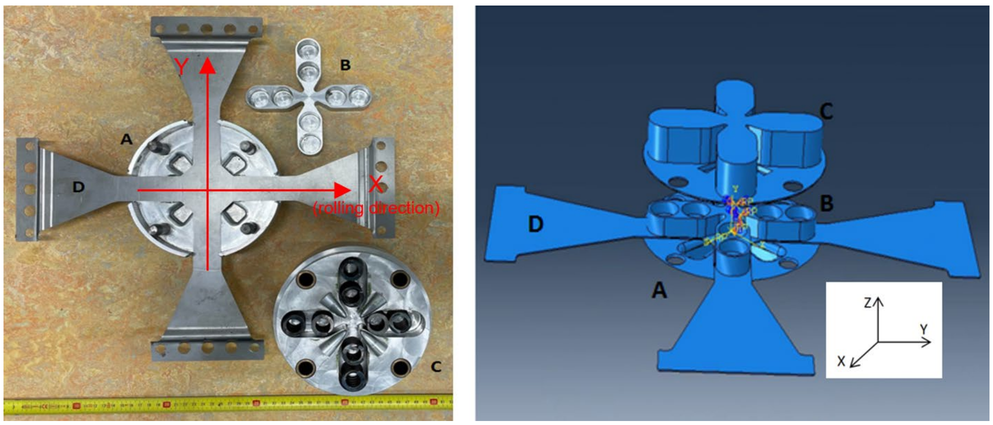

Fig. 6. Components of punching die and view of the 3D model assembly:

A - base part; B - cross holder; C - upper part; D - 0.5 mm cruciform sample.

In the FE model, the different tools are considered rigid. Only the cruciform specimen is considered deformable (C3D8R element type). Tangential contact behaviour is applied for all the contact areas during the punching process. The frictional coefficient is assumed to be 0.1. A refined mesh size of 0.5 mm is defined in the gauge area. Fig. 7 gives the distribution of the plastic equivalent strain at the surface of the specimen at the end of the first step. One can notice that the centre of the specimen does not deform during the punching process of Step 1. For Step 2, a damage evolution criterion [9], calibrated from the uniaxial test (Fig. 2), is introduced.

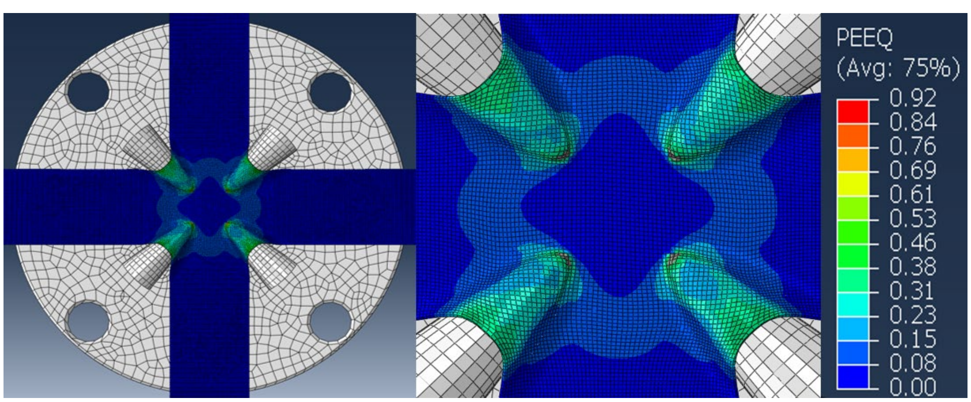

Fig. 7. Plastic equivalent strain distribution at the end of Step 1.

Results and Discussion

As mentioned before, three loading conditions (cases 1 to 3) are studied. The following figures (Figs. 8 to 10) show the comparison between experimental and predictive in-plane strain components ε_{11} and ε_{22} along the two perpendicular directions X and Y defined in Fig. 6 respectively. The time for the comparison corresponds to the onset of necking in one of the four arms.

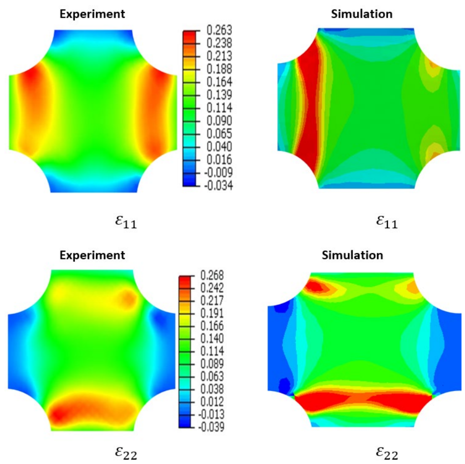

Fig. 8. Case 1 – Biaxial stretching.

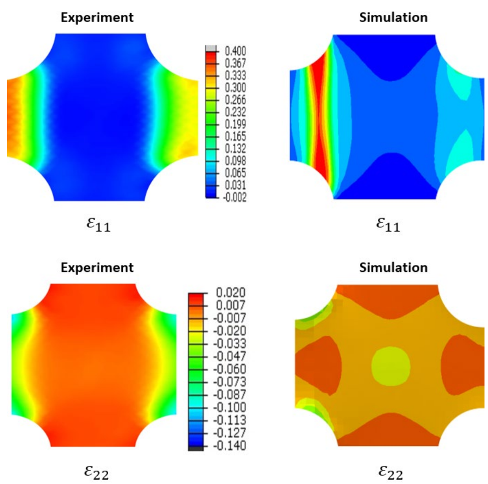

Fig. 9. Case 2 – Near plane strain condition.

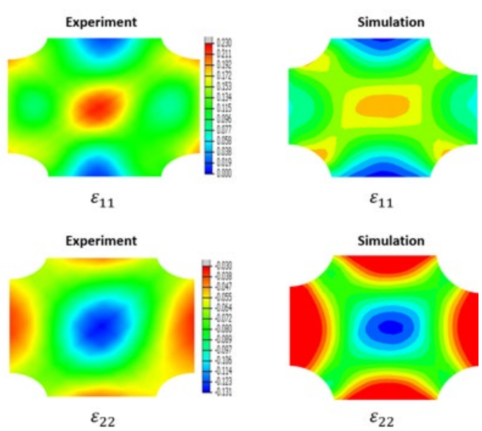

Fig 10. Case 3 – Uniaxial stretching.

Figs. 8 to 10 show a similarity in the strain distribution between the experimental and the predictive results. For cases 1 and 3, the level of strain measured at the centre of the sample is rather high. It leads to values of equivalent strain similar to or higher than the ones measured in the uniaxial test. This is an essential result for the use of this cruciform shape for mechanical characterization (hardening behaviour or anisotropy). The evolution of major and minor strains (in-plane principal strains) can be plotted for the three loading conditions. The comparison of the maximum equivalent strain (failure strain) values for three cases is shown in Table 1. The maximum equivalent strain values represent the starting of the structural failure. The quantitative comparison between simulated and experimental strains at the specimen center can reach up to 30% depending on the considered condition. Fig.11 compares the strain paths for three cases between experimental and numerical results. As expected, the three loading conditions lead to very different strain paths. For this cruciform shape, the strain path measured at the centre of the sample is directly linked to the ratio of actuator velocities. Moreover, as already observed for cruciform samples with reduced thickness [5], the strain paths for the three cases are quasi-linear.

Table 1. Comparison of maximal strain values between experimental and numerical study at the centre point of the specimen.

	Experiment		Simulation		Difference	
	$\varepsilon 11_{max}$	$\varepsilon 22_{max}$	$\varepsilon 11_{max}$	$\varepsilon 22_{max}$	$\Delta\varepsilon 11_{max}[\%]$	$\Delta\varepsilon 22_{max}[\%]$
Case1 [Biaxial stretching]	0.132	0.121	0.109	0.080	17.4	33.9
Case2 [Plane strain]	0.075	-0.019	0.052	-0.023	30.7	21.1
Case3 [Uniaxial stretching]	0.276	-0.159	0.191	-0.129	30.8	18.9

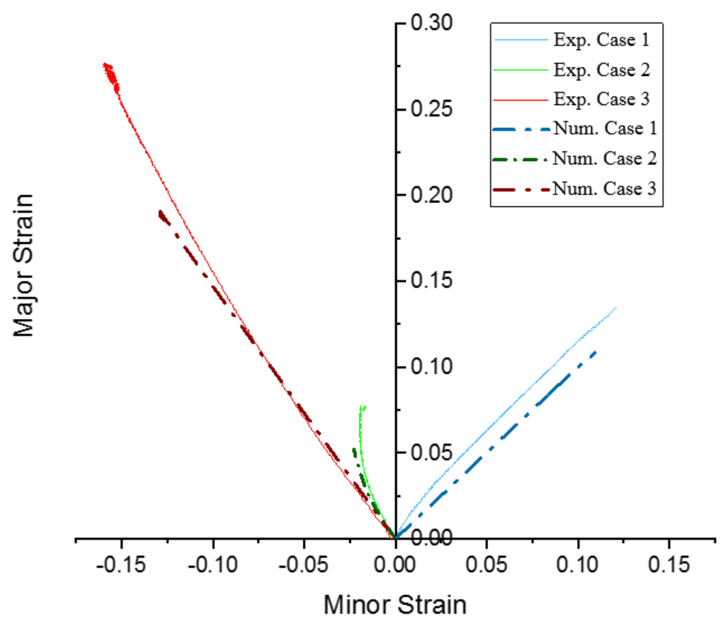

Fig. 11. Comparison of the strain paths for the three loading conditions.

Summary

A numerical model of the forming and testing of an original cruciform sample, without local thickness reduction, was proposed. This cruciform sample was subjected to three different loading conditions (biaxial stretching, near plane strain condition, and uniaxial stretching) in order to evaluate the potential of this sample to characterize advanced mechanical behaviour for different strain states. The predictive qualitative results from the FE model are in agreement with the strain fields measured during the tests for the same loading conditions however the quantitative comparison between simulated and experimental strains at the specimen center can reach up to 30% of difference depending on the considered condition. Specimen geometry and the dimensions of the preforming die were obtained through FE analysis by a limited number of comparisons. Since the character of the deformations obtained from simulation and experiments is similar, the current numerical model can be used for further optimizations of the proposed geometry in order to emphasize the strain localization at the gauge region and use the sample for mechanical characterization at high strain level (hardening behaviour or forming limits).

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