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Insights into Cruciform Sample Design

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Abstract

Four different cruciform sample designs, based on the work of Abu-Farha et al., were studied in this paper. Key features of this design are a recessed pocket with fillet and re-entrant corners. These samples were shown via digital image correlation to achieve widely differing strain values inside and outside the pocket. From the results of these tests, there are two competing failure mechanisms in the sample. The pocket region is affected by stress concentrations caused by the fillet, and re-entrant notches lead to strain limited constraints similar to diffuse and localized necks in uniaxial samples. Balancing these two constraints determines the success or premature failure of the sample.

Introduction

As the automotive industry moves to new lightweight alloys and composites for vehicle bodies, there is a considerable activation barrier in learning how to manufacture components out of these materials. To date, designers have relied on the design models using empirically-trained material constitutive laws that are calibrated using fairly simplistic mechanical tests. Uniaxial data aligned at various angles with respect to the rolling direction, combined with bulge test data and forming limit determinations, are extrapolated using multiaxial yield models to determine the shape of the yield surface in stress space. This

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limited experimental information can give misleading predictions on how the yield surface evolves with plastic strain. Tests on an 5754 aluminum alloy [1], [2], with a revised stress-stress plot developed in [3], showed measured multiaxial stresses in samples loaded along a series of linear strain paths to near failure. The measured yield surface shape evolves in ways that are not currently modeled, including non equal-biaxial stress for equal-biaxial strain.

However, the sheet metal forming limit test apparatus used in the cited references could only strain along linear paths, and data are needed for more complex strain paths, including changes in strain path direction. Cruciform tests can fill this role. The NIST Center for Automotive Lightweighting (NCAL) [4] has developed an advanced cruciform formability system [5] that can apply multiaxial, non-monotonic strain paths to a material, while independently measuring the resulting stresses and surface strains in the sample.

There have been a large number of cruciform sample geometries and testing frames developed and discussed in the literature (see citations in [5], as well as [6,7,8,9,10] as examples). These geometries are often designed for a specific material, test matrix, and/or machine. More challenging requirements are: 1) failure occurs near the center of the sample, 2) failure occurs near the center at the limit strain of the material and, 3) the strain distribution in the center of the sample is uniform.

The cruciform sample geometries presented here use the “N225D635” design of Abu-Farha et al [11] as a starting geometry. This sample geometry was chosen as it was reported to fail in the center region of the sample, albeit when combined with elevated temperature in the center region. The experiments described below test the following hypotheses:

- The geometry described in [11] will fail in the center without heating the sample.
- The geometry described in [11] can be modified to permit testing on thinner materials.
- Digital image correlation (DIC) data will show sample deformation that leads to sample failure.

Cruciform Testing Machine and Procedure

The specific capabilities of the NCAL cruciform frame have been described in [4] and [5] but will be summarized here. This cruciform testing frame has four independently controllable actuators with a ± 500 kN capacity and ± 50 mm stroke. Each actuator pair can be independently controlled in displacement, force or strain, with the ability to switch between these modes during testing without unloading. The deformation is recorded using two sets of 3D surface digital image correlation (DIC) cameras, and an additional 2D DIC camera that provides real-time strain monitoring and control. Additional capabilities of thermal imaging and *in-situ* x-ray diffraction for stress measurement and phase analysis are available, but were not used for the tests described in this paper.

Cruciform Samples

Four variations of cruciform samples were developed and tested. Figure 1 is a schematic showing the key dimensions of these samples, and Table 1 provides the values of the dimension for each sample. Samples were deformed in displacement control with equal displacements on each arm. The strain rate was approximately 4×10^{-4} for each test. The samples were loaded to fracture of the sample.

Sample 1 scaled all dimensions given in [11] by a factor of 3, attempting to match the three-dimensional shape of the geometry given in [11]. The thickness of Sample 1 required plate material instead of sheet. With the exception of the Lüders banding observed in the hot rolled plate, it is expected that this material will have a similar low work hardening deformation behavior to the cold-rolled sheet used in the remainder of the samples. For Sample 2, the T_{sample} , T_{pocket} , and F_{pocket} were reduced by a factor of 3 compared to Sample 1. This made it possible to fabricate it from 11 gauge cold-rolled sheet steel. For Sample 3, the W_{arm} , D_{notch} , D_{pocket} and L_{N2P} were scaled up from Sample 1 to match the largest grip face size (200 mm) available on our machine, which maximizes the size of the flat bottom of pocket region. An end mill was used due to the size of the pocket in Sample 3. This geometry was previously used for the more complicated deformation paths, shown as Examples 1 and 2 in [5].

The series of dimensional changes between Samples 1, 2, and 3 were based on scaling a subset of the key sample dimensions. Based upon the results of these experiments (described below), the geometry of Sample 2 was used as a baseline for finite element analysis (FEA) based optimization. After validation of the post uniform elongation (see [12], [13] for details) optimization for the highest center strain was performed to create sample ‘Opt’. In this optimization the dimensions for T_{pocket} , D_{pocket} , L_{N2P} , and F_{pocket} were allowed to vary from those used in Sample 2, while the other dimensions were held fixed. Details of the optimization process will be described in a future work.

Results

As mentioned previously, the ideal cruciform geometry would result in failure in the pocket and a uniform region of deformation in the pocket prior to failure. As the four samples tested are from the same ‘family’ of cruciform geometry, one may expect that the deformation would also be similar. That is not what was observed, particularly in the case of the strain distribution in the samples. Typically strain distributions are not shown in the literature, but are critical for understanding the sample deformation, particularly in materials with high elongation before failure.

No established method currently exists for comparing cruciform geometries. Owing to the differences in geometry, the mechanical response of each sample was different. To compare strain distributions, the peak force was taken as a reference point for each sample. The Von Mises effective strain (including elastic and plastic strains) was calculated from the DIC data. An average strain was calculated from an area inside the pocket. To avoid effects from

the fillet, only strain values inside a radius one half of the distance from the center of the pocket to the beginning of the fillet were used.

As the strain distribution at peak force already includes significant localization of the deformation, an intermediate deformation step was chosen for comparison. From the average strain value at peak force, 90% of this average strain value was calculated. The DIC image closest to 90 % of the strain at peak force was selected for further study, and is referred in what follows as $t_{90\%}$. Values for peak force and strain at $t_{90\%}$ can be found in Table 2. A snapshot of the strain distributions at $t_{90\%}$ for each sample is shown in Figure 2. Strain values were extracted from the DIC data along a path midway between the notch and pocket (shown as Arc B in Figure 1).

Comparing the strain profiles of Sample 1, 2, and 3 (the top row of Figure 2), Sample 1 has the highest average strain in the pocket (solid black line), but a wider variation of strains inside the pocket (dashed black lines), than Samples 2 and 3. The strain in the center (black lines) of Sample 1 is also larger than the maximum of the strain profile (red) between the notch and pocket. In Sample 2 the maximum of the strain profile and average strain in the pocket are about the same and for Sample 3 the maximum of the profile is substantially larger than the average strain in the pocket. At $t_{90\%}$, the strain profile for Sample 3 (Figure 2c) between the notch and pocket seems to be two superimposed peaks, one with a smaller half-width than the other, as evidenced by a change in curvature at approximately ± 15 mm.

In the second row of Figure 2 the spatial relationships of the strains are shown. Sample 1 shows more strain variation in the pocket than Samples 2 and 3, with larger values in the center and where the fillet meets the bottom of the pocket forming an “X” pattern. Sample 2 shows the largest strains only near where the fillet meets the bottom of the pocket. In Sample 3, there was little strain in the center of the sample, most of the deformation occurred near the notches or in a ring near the fillet. Unlike Samples 1 and 2, Sample 3 failed between the notch and pocket.

The Opt Sample resulted in center strains that were greater than Sample 2 and comparable to Sample 1. Similar to Sample 1, the strain in the pocket was larger than the strain between the notch and pocket. Additionally, the strains at the ends of the profile are also non-zero like Sample 1. Like Samples 1 and 2, failure occurred in the pocket near where the fillet is tangent to the bottom of the pocket.

These four samples showed a range of different strains in the pocket, despite being derived from the same geometry [11]. The main differences between Sample 1 and 2 were dimensions for T_{sample} , T_{pocket} , F_{pocket} and sample material. In Sample 2 and the Opt sample the material was the same, but the T_{pocket} , D_{pocket} , L_{N2P} , and F_{pocket} dimensions were different. Based on the results shown, these seem to strongly affect deformation, but the mechanisms for these effects are not clear. A central question posed by these results is to determine what characteristics of these samples created these differences.

Discussion

Samples 1, 2, and Opt approach the ideal of larger strains in the pocket than anywhere else in the sample, a uniform region of deformation in the pocket and failure in the center of the sample. Failure occurred in the pocket of Sample 1, showing that the sample geometry presented in [11] will fail in the pocket at room temperature. The comparable strains in Sample 1 and Opt indicate that it is possible to create cruciform samples that fail in the pocket from thinner materials.

Abu-Farha and co-authors postulate that the pocket behaves similar to the section of reduced area in uniaxial tests [11]. In a uniaxial test, this reduction in area increases stress and concentrates deformation away from the tab region. Applying this observation to cruciform samples, the increase in stress would be comparable to the $T_{\text{sample}}/T_{\text{pocket}}$ ratio. As shown in Table 2 the optimized sample has a larger ratio, and therefore higher stress in the pocket. This ratio alone does not explain the sample behavior, as this ratio in Sample 2 is greater than Sample 1.

In addition to the change in stress due to the reduction of area, a fillet will also result in a stress concentration where the tangent of the fillet meets the bottom of the pocket. If the F_{pocket} dimension is not chosen judiciously, the stresses at the end of the fillet will be significantly larger than the center of the pocket. A higher stress near the fillet can be inferred from the larger strain values near the fillet in all the samples, and the location of sample failure in Samples 1, 2, and Opt. The stress concentration factors were calculated using linear elastic solutions (pages 782–784 of [14], pages 80–88 of [15]) and listed in Table 2. The values for Sample 1, 2 and 3 are similar, while the value for the optimized sample is much lower, but still 15 % higher than in the center of the pocket. These stress concentration effects may explain why failure occurs right at the point where the fillet meets the pocket bottom, as observed in Samples 1, 2, and Opt, and shown in the DIC images shown in Figure 10 of [11]. One method to reduce the stress concentrations would be to increase F_{pocket} , but this would be impossible for a sample fabricated via welding or gluing multiple stacked sheets.

The region between the notch and pocket also shows significant strain. In a cruciform sample, the stress state immediately adjacent to the notch can be approximated by uniaxial tension. In uniaxial tests of steel and other ductile materials, the post uniform elongation behavior is typically divided into two regimes, diffuse necking [16] and localized necking [17]. As the strains in this region are high, they are likely in these necking regimes. Diffuse necking is said to begin when the gradient in area reduction matches the gradient in strain hardening [16]. Referencing the uniaxial case, partial derivatives of each term of the cross-sectional area show that the gradient will be affected by both thickness and width. If isotropy is assumed, the gradient in area will be dominated by the larger of the width or thickness. Localized necking is defined by a jump in velocity (strain rate) of the material, and depends on the smaller dimension as derived for the thickness of sheet materials ($w \gg t$) [17].

In the case of the cruciform geometries shown here, the relevant dimensions approximating cross-sectional area would be T_{sample} and L_{N2P} . Table 2 lists the larger of T_{sample} and L_{N2P}

and the full width half max (FWHM) of the strain profiles, showing that these values are similar. This indicates that the deformation in the notch to pocket region is in a state of diffuse necking, and the length scale of the diffuse necking is key to how the overall cruciform deformation will proceed. While Sample 3 does not seem to follow the trend, a localized neck had developed prior to $t_{90\%}$, as evidenced by the change in curvature at approximately ± 15 mm. Prior steps in the deformation ($\approx t_{50\%}$) show a FWHM closer to 30 mm, in agreement with the trend.

Finite element analysis that accurately captures the diffuse neck shape is challenging, as shown in [12] and [13]. As diffuse necking is governed by strain hardening behavior and/or strain rate sensitivity, this may explain why cruciform samples developed for steel rarely work well for aluminum or other materials. Detailed finite element analyses of these geometries are planned and should illuminate what level of detail is required for accurate prediction of cruciform sample deformation.

Conclusion

The original sample design of Abu-Farha *et al.*, was tested at room temperature and lead to failure in the center of the sample. Based on this geometry, three derivative cruciform sample designs were shown via DIC to achieve widely differing strain values inside and outside the pocket. The relative proportions of the F_{pocket} , T_{sample} , and L_{N2P} dimensions strongly affect the strain in the pocket. The fillet results in a stress concentration, minimization of which allows adjacent areas to deform and stave off fracture. The region between the notch and pocket deforms in a similar manner to a uniaxial test; with strain limited behavior akin to diffuse and localized necks forming. Balancing these stress and strain limited constraints by the sample geometry determines the success or premature failure of the sample.

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Figure 1. Schematic of cruciform geometry and definitions of dimensions. Arc B depicts the location of strain values shown in Figure 2. Length of each cruciform arm L_{arm} is not shown.

Figure 2.

Plots at 90 % of the strain at peak force ($t_{90\%}$): (letters a, b, c, and d on the top row) von Mises Hencky strain profiles at along Arc B in Figure 1, with average pocket strain and variation (black lines); (letters e, f, g and h on the bottom row) images showing DIC measured von Mises Hencky strain field overlaid on the image. Columns show the same sample (for example, Sample 1 is shown in a and e)

Table 1

Cruciform sample geometries. All dimensions are in mm. Range of values ($\pm$) are the larger of one standard deviation of the measured values or the precision of the measurement. The column “Abu-Farha” contains values from [11] and are provided for reference. Material specifications are from American Iron and Steel Institute (AISI) and ASTM International. Pocket fabrication method was either an electrical discharge machining (EDM) punch or milling with a 1 mm fillet radius end mill.

	Abu-Farha [11]	Sample 1	Sample 2	Sample 3	Opt
T_{sample}	3.2	9.38 ± 0.05	2.9 ± 0.1	3.0 ± 0.1	2.931 ± 0.004
W_{arm}	9.53	28.6 ± 0.1	28.6 ± 0.1	$200. \pm 1.0$	28.59 ± 0.11
L_{arm}	19.1	$266. \pm 1.0$	$266. \pm 1.0$	220 ± 10.0	$266. \pm 1.0$
T_{pocket}	1.0	2.89 ± 0.01	0.749 ± 0.001	1.0 ± 0.1	0.628 ± 0.005
D_{pocket}	6.35	18.7 ± 0.3	19.1 ± 0.1	132.1 ± 0.1	14.05 ± 0.04
F_{pocket}	1.59	4.76 ± 0.40	1.2 ± 0.4	1.0 ± 0.1	3.18 ± 0.25
D_{notch}	3.18	9.5 ± 0.1	9.5 ± 0.1	$60. \pm 1.0$	9.5 ± 0.1
L_{N2P}	$2.05^{\dagger}$	6.07 ± 0.1	5.875 ± 0.1	30.5 ± 0.1	8.38 ± 0.1
Material Specification		ASTM A36 Hot rolled Plate	ASTM A1008 CS B Cold rolled sheet	AISI 1015/10 Cold rolled sheet 20	ASTM A1008 CS B Cold rolled sheet
Pocket Fabrication Method		EDM	EDM	Milled	EDM

[†]This value is ambiguous in the referenced paper, as it is overdetermined from the depth of corner notch dimension. We estimated this value to be 2.05 mm.

Table 2

Summary of Results. The full width half maximum (FWHM) value uses only the peak height (background is removed) to calculate the half maximum value.

	Sample 1	Sample 2	Sample 3	Opt
Peak Force	71.4 kN	13.4 kN	88.6 kN	18.0 kN
Center Strain at $t_{90\%}$ *	0.262 ± 0.005	0.156 ± 0.003	0.082 ± 0.003	0.246 ± 0.011
$T_{\text{sample}}/T_{\text{pocket}}$	3.24	3.91	3.10	4.67
Stress concentration factors	1.29	1.32	1.38	1.14
Larger of L_{N2P} or T_{sample}	9.4 mm	5.9 mm	30.5 mm	8.4 mm
FWHM in profile at $t_{90\%}$	10.4 mm	5.1 mm	$19.1 \text{ mm } (\approx 30 \text{ mm})^{\dagger}$	5.9 mm

*
± one standard deviation

[†]The FWHM value is lower because the sample has formed a localized neck at $t_{90\%}$. Analysis of earlier images show a FWHM ≈ 30 mm.