journal of materials processing technology 198 (2008) 1–13

journal homepage: www.elsevier.com/locate/jmatprotec

Review

A review of planar biaxial tensile test systems for sheet metal

*Alan Hannon, Peter Tiernan**

Manufacturing & Operations Engineering Department, University of Limerick, Limerick, Ireland

ARTICLE INFO

Article history:
Received 29 March 2007
Received in revised form
18 September 2007
Accepted 8 October 2007

Keywords:
Biaxial
Testing
Sheet metal
Cruciform
Specimens

ABSTRACT

The focus of this paper is to present a comprehensive review of the main biaxial test systems that have been developed with primary focus on sheet metal testing. The paper includes a review of biaxial tensile test devices and specimen design for biaxial testing. A description of the scientific significance of the work and the industrial implications arising from results of biaxial testing is also presented.

Biaxial testing of metal is becoming prevalent in the sheet metal working industry for establishing the mechanical properties of the sheet material. The primary reason for using the biaxial tensile test, as opposed to the common uniaxial test, is that metal in sheet form is largely anisotropic, i.e. it has varying mechanical strength in different directions due to the forming process used in its manufacture. As the standard tensile test only determines the mechanical properties in one direction the resulting test data may not be applicable to multi-directional forming processes such as deep drawing. Biaxial testing is also becoming increasingly important for testing of metals used in machine and structural components that may be typically loaded in more than one direction during service. Biaxial loading can cause failure of the material at loads much less than that determined by conventional tensile-testing methods. The aforementioned reasons have led to research activity in the area of biaxial testing.

Contents

* *Corresponding author*. Tel.: +353 61 213503; fax: +353 61 202913.
E-mail address: peter.tiernan@ul.ie (P. Tiernan).

0924-0136/$ – see front matter
doi:10.1016/j.jmatprotec.2007.10.015

1. Introduction

Sheet metal forming processes are among the most important metal working operations (Green et al., 2004). These processes account for a sizeable proportion of the manufactured goods made by industrialized countries each year. Frequently, the metals used in these forming processes have limited formability. Thus, a thorough understanding of the deformation processes and the factors limiting the forming of sound parts is important, which contributes to faster product development at a lower cost and with enhanced product quality (Klaus and Gerlach, 1998).

In sheet metal forming operations, the amount of useful deformation is limited by the occurrence of unstable deformation, which mainly takes the form of localized necking or wrinkling. Failure by wrinkling occurs when the dominant stresses are compressive, tending to cause thickening of the material. Localized necking occurs when the stress state leads to a decrease of the surface area of the sheet at the cost of a reduction in the thickness. Sheet metal used in forming processes is typically accompanied by data that defines the behavior of the material when it is subjected to mechanical loading. This important data, which usually includes material yield strength, tensile strength and work hardening exponent is typically obtained from a standard uniaxial tensile test. As most metal forming operations are carried out under biaxial states of stress, the stress–strain formability parameters obtained by uniaxial tensile testing are inadequate for the application to deformation induced under states of biaxial stress (Jones, 2001). Consequently, biaxial testing has become of great importance in establishing the formability characteristics of sheet metal where the material is subjected to deformation in more than one plane or axis. Furthermore, many manufacturing materials exhibit anisotropic properties for which in-plane biaxial testing of cruciform (cross-shaped) specimens is important for deriving mechanical properties used in the determination of a material' s formability (Demmerle and Boehler, 1993).

Biaxial tensile testing is also becoming increasingly common in determining the mechanical properties of materials used in aircraft structural components, bridge support sections, machine components, etc. (Jones, 2001). In service, these components are normally loaded in more than one direction at once, i.e. biaxially loaded. It has been recognized that limiting the evaluation of a material's mechanical characteristics to uniaxial coupon tests can lead to a misrepresentation of the behavior of a material in an engineering structure (Jones and Green, 2001). However, by the use of more realistic loading during the test such as the introduction of biaxial loading conditions leads to a more accurate representation of the expected behavior of the structure in-service (Ohtake et al., 1999).

Among the experimental methods in use, biaxial tensile testing with various types of cruciform specimens has become the most promising method to produce stress states of biaxial tension by changing proportion of load or displacement of two axes (Xiang-Dong et al., 2005). The most important part of a biaxial testing system is the design of the cruciform specimen. To enable the acquisition of full stress–strain curves, the center section of the specimen must experience elastic and plastic deformation. Although specimens of the cruciform type have been investigated quite extensively, no standard geometry exists for the specimen design (Lin et al., 1993; Lin and Ding, 1995).

2. Material testing

One of the most important concerns when selecting a material for a machine component is to ensure that the material properties are appropriate for the operating conditions of the component (DeGarmo et al., 1997). Materials have both physical and mechanical properties and the most common way of distinguishing one material from another is by evaluating their physical properties (Groover, 2002). These would include such characteristics as density, melting point, optical properties (color, etc.), thermal properties of specific heat, coefficient of thermal expansion and thermal conductivity, electric conductivity and magnetic properties. In some cases these may be of prime importance but more often, the properties that describe how the material responds to applied loads or forces assume the dominant position in material selection, i.e. mechanical properties. These properties include elastic modulus, ductility, hardness and various measures of strength. Mechanical properties are very important in design because the function and performance of a product depend on its capacity to resist deformation under the stresses encountered in service. When choosing a material these properties are usually readily available but they must be understood by the engineer. The engineer must know what values are significant, what limitations should be in place and how these values were determined. To understand these, the engineer must be familiar with the various test procedures that were used to collect this data. One restriction that must be understood is that mechanical properties are usually determined by a testing a specimen in a laboratory. Caution must be taken as the conditions of the test in the laboratory rarely duplicate the service conditions.

When a force or stress is applied to a component, the material is deformed (strained) (DeGarmo et al., 1997). There are three types of static stress to which materials can be subjected: tensile, compressive and shear. Tensile stresses tend to stretch the material, compressive stresses tend to squeeze the material and shear stresses tend to cause adjacent portions of the material to slide against each other (Groover, 2002). The stress–strain curve shows the basic relationship that describes all three types. The most commonly used test to calculate these curves is the uniaxial tensile test.

3. Biaxial testing

The mechanical properties of materials under uniaxial stress are used to estimate the strength and deformation of the components in the design of a machine or structure. The assumption that loads act in one direction is a simplification that works well, to a point. In service conditions, however, loads are simultaneously applied in several directions, producing stresses with no bias to a particular direction (Pun, 2003). In service, for example, blow moulded mechanical components are normally loaded in more than one direction at once (Martin et al., 2005), i.e. they are biaxially loaded. Also many structures, e.g. aircraft and spacecraft components are often subjected to multi-axial stresses (Johnston et al., 2002). Generally, multi-axial stresses and strains in high temperatures components cannot be described by uniaxial data (Samir et al., 2006). It has been recognized that limiting the evaluation of a material characteristic to uniaxial coupon tests can lead to a misrepresentation of the behavior of a material in an engineering structure (Martin et al., 2005). The uniaxial tensile test yields the ranking of relative formability among various sheet alloys. However, the true fracture strain observed in the uniaxial case is far less than the corresponding value encountered in the biaxial case and hence, the uniaxial tensile test may underestimate the formability in a practical forming operation (Li and Ghosh, 2004). By using more realistic loading during the test, i.e. introducing biaxial loading conditions, will yield a more accurate representation of the expected behavior of the structure in service (Jones, 2005). The stresses acting on a component in service are generally multi-axial in nature. Therefore, it is necessary to consider the mechanical properties not only under uniaxial stress states but also under these multi-axial states of stress (Ohtake et al., 1999). In recent years, tests have been designed in an attempt to produce forces that are closely related to those that the material is subjected to during normal service conditions. Biaxial tensile tests can be used to produce forces that occur in more than one direction simultaneously. From this test, stress–strain curves can be produced for different directions of the test specimen. A survey of the literature reveals that relatively few experimental investigations have been carried out to characterize sheet metals under biaxial tension (Green et al., 2004). There are numerous methods of producing biaxial stresses in material for different types of specimens. These include the bulge test (Altan, 2003; Vlassak and Nix, 1992), combined tension–torsion test (Keefe et al., 1998), combined bending and in-plane test (Soni et al., 2003) and biaxial testing of sheet metal.

3.1. Biaxial testing of sheet metal

One of the most frequently used material forms is sheet metal. It is becoming increasingly important to test sheet metal under conditions of multi-axial loading as the material is commonly formed under multi-axial states of stress. Biaxial testing with various types of cruciform specimens has become the most promising method to realize various stress states of biaxial tension by changing proportion of load or displacement of two axes (Xiang-Dong et al., 2005). Furthermore, the standard uniaxial test is accurate only for isotropic materials. As thin plates are manufactured by rolling, they tend to exhibit anisotropy in their tensile properties (Schodel et al., 2006). For non-isotropic materials like sheet metal, the results of a standard tensile test can lead to either over-designed or under-designed components or structures. Consequently, new methods of mechanically testing sheet metal are required. Test machines that have being developed to produce multi-axial loading include:

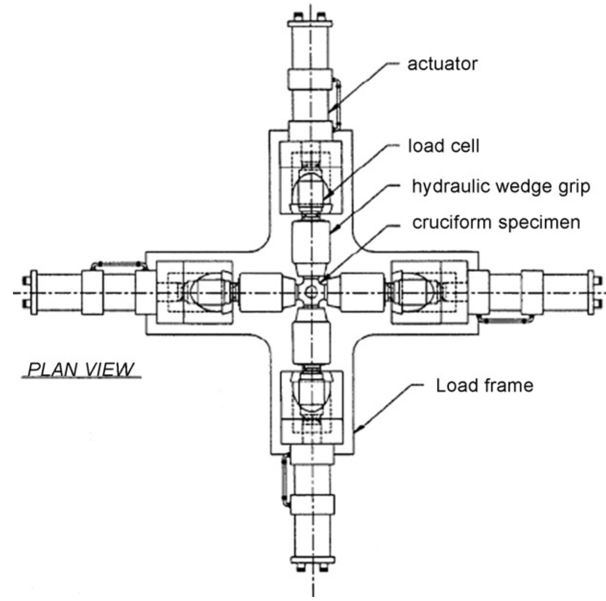

Fig. 1 – Biaxial testing machine for cruciform specimen (Makinde et al., 1992a).

- Stand-alone biaxial testing machines
- Link mechanism attachments for biaxial testing.

3.2. Stand-alone biaxial testing machines

A biaxial test machine designed by Makinde et al. (1992a) is presented in Fig. 1. The device consisted of two main sections: the loading system and the control system. The loading system design consisted of an out-of-plane configuration as shown in Fig. 1. Due to the fact that the frame was subjected to large stress, the construction was over designed to reduce any deflection within the frame. Two linear hydraulic actuators with a rated capacity of 250 kN were mounted on the rigid frame along both axes. Two actuators were used on both axes to ensure that the center of the specimen did not move during testing. Also, both opposing hydraulic actuators were connected to common lines to ensure that they exerted an equal but opposite force on each other. A load cell was used in each axis to measure the force in both directions throughout the test. Grippers were also designed and manufactured which could be preloaded and locked prior to testing. This biaxial test machine has been used to test various types of cruciform specimens at both small and large strains. The results from this research were used to develop an optimum specimen for low strains. A number of pilot tests on cruciform metal specimens loaded biaxially were successfully carried out. The researchers used the apparatus to estimate the degree of non-uniformity of strain inside the gauge length of various cruciform specimens proposed by other researchers as shown in Fig. 2.

A further stand-alone device was developed by Boehler et al. (1994) to produce a biaxial force. It consisted of four double acting screw driven pistons, which were mounted, on an octagonal vertical frame. Two double acting screw driven pistons in each direction ensured that the center of the specimen did not move during the test. Two motors controlled each

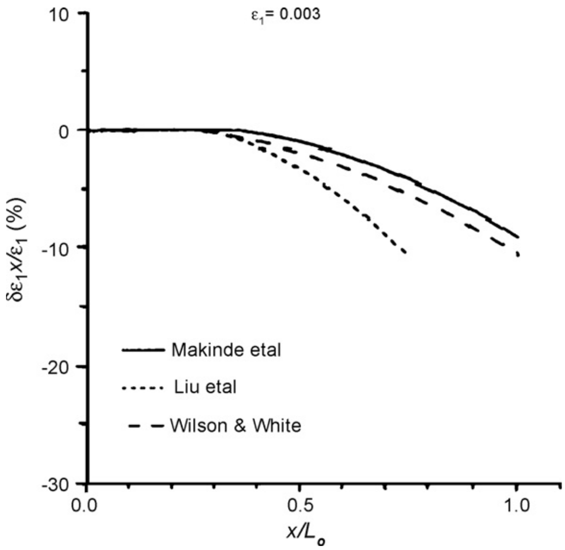

Fig. 2 – Estimation of the degree of non-uniformity of strain inside the gauge length for three cruciform specimens (Makinde et al., 1992a).

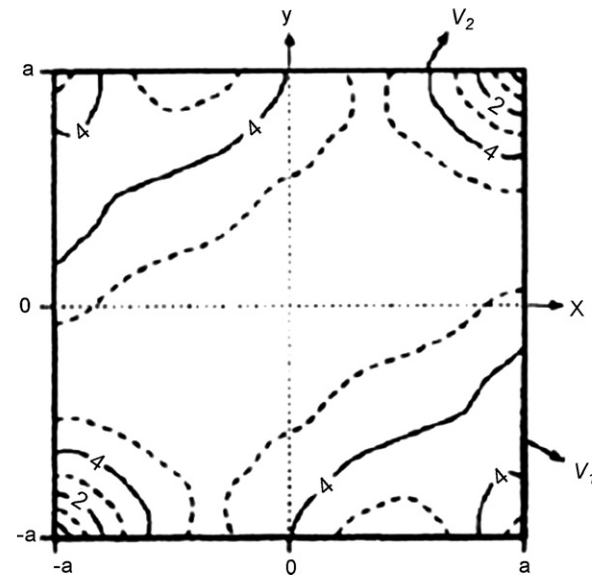

Fig. 3 – Isostress lines for σ_{xy} inside test section of the optimized rigidly clamped specimen (Boehler et al., 1994).

screw. One variable dc motor was used during testing and a high-displacement ac motor for positioning prior to testing. Also each motor incorporated a clutch to prevent both engaging simultaneously. It was possible to vary the test speed between 0.003 and 0.3 mm/min. The maximum load that could be produced was 100 kN in both directions. The advantages in using the vertical frame are that it facilitated excellent access from both sides allowing ease of mounting the specimen. Also it allowed good observation throughout the test for photography or to analyze the strain field by the laser or video method. A disadvantage of this method was that the dead weight of each of the horizontal gripper and assembly arrangements must be taken into account to minimize side bending on thin specimens. This machine was used to test various cruciform specimen types in an attempt to develop an optimum specimen design. Specimen design considered by Boehler et al. is presented in Section 4. The researchers used finite element analysis to compare an optimized specimen with previously designed specimens. Both rigid-clamped and off-axes testing were performed on the optimized specimen for anisotropic elastic materials. The numerical model was used to provide a prediction of the shear stress field in the gauge area of the specimens. A plot of the isostress lines inside the test section for the optimized specimen is presented in Fig. 3. Weak gradients are exhibited in this plot for the optimized specimen. The value in the center of the test section is $\sigma_{xy} \approx 5.8$ MPa. Thus the authors conclude that when testing with rigid clamps on anisotropic materials, the obtained data cannot be useful to identify constitutive laws because the principle axes of the obtained biaxial stress field cannot be determined.

Kuwabara et al. (1998) completed a study to clarify experimentally, the elastic and plastic deformation behavior of cold rolled low-carbon steel under biaxial tension. To complete this experiment, a newly constructed biaxial tensile-testing apparatus was manufactured. The biaxial tester was of a servo type and the main components of the setup are shown in Fig. 4.

Opposing hydraulic cylinders were connected to common hydraulic lines so that the same hydraulic pressure was applied to each. Each of these opposing hydraulic lines was controlled independently using servo control. As with two previous devices, one important factor was to maintain the center of the specimen stationary throughout the test. This was achieved by using a pantograph-type link mechanism as shown in Fig. 4. This method proved to be a very effective method and reduced the cost of the apparatus significantly. A load cell was used in each direction to calculate the stress in the specimen. The strain was calculated using strain gauges, which were placed, in the gauge section of the specimen. The outputs from both load cells and the strain gauges were mon-

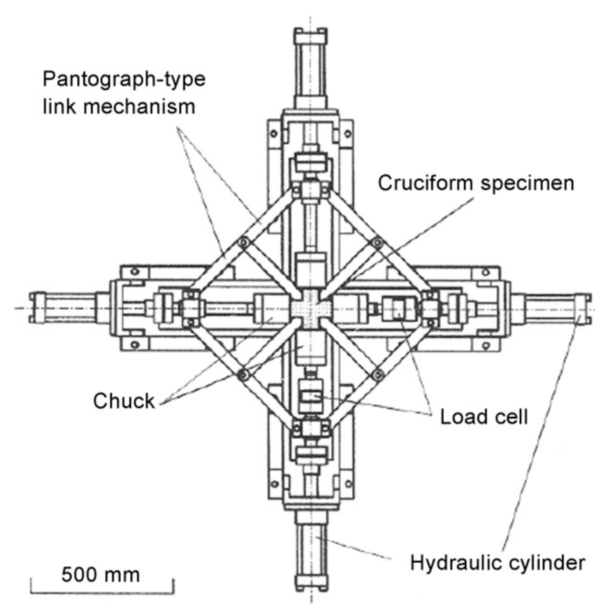

Fig. 4 – Horizontal biaxial tensile tester (Kuwabara et al., 1998).

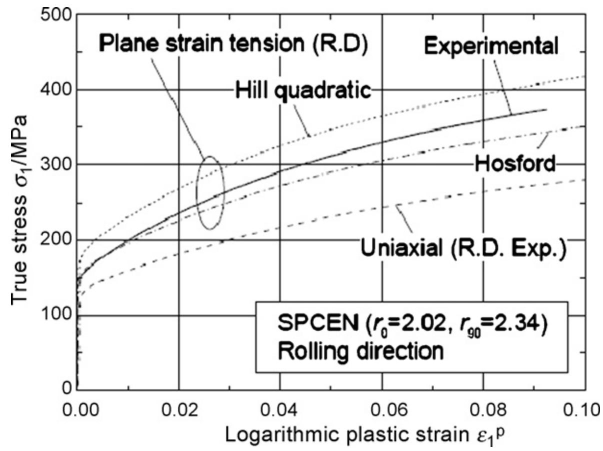

Fig. 5 – Stress vs. strain plot for SPECEN steel (Kuwabara and Ikeda, 2002a,b).

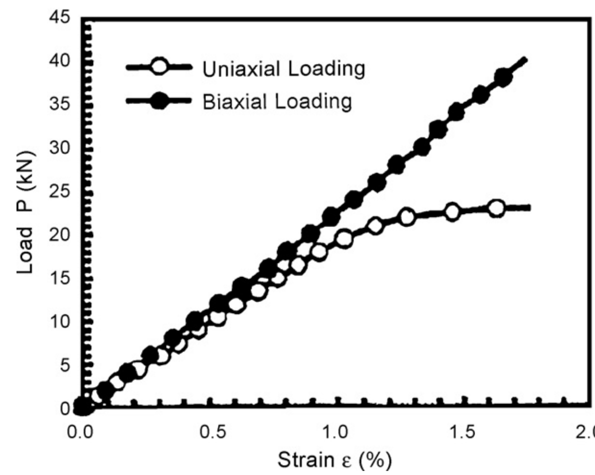

Fig. 6 – Relationship of load and strain for uniaxial and biaxial loading (Shimamoto et al., 2003).

itored using PC based data acquisition. This setup was used to test ultra low carbon steel (SPECEN) cruciform specimens and to compare the results with existing yield criteria (Kuwabara and Ikeda, 2002a,b) as shown in Fig. 5. It was observed that the measured flow stresses were in good agreement with those predicted by Hosford's yield criterion.

Shimamoto et al. (2003) have developed and validated a biaxial testing rig to carry out various types of biaxial tests. This rig had the capability to perform both dynamic and static tests at controlled temperatures. This biaxial tensile tester was of a horizontal configuration. The applied load was measured using a load cell in each direction and strain gauges were used to measure the strain. Hydraulic actuators were used to perform the test. This ensured that the hydraulic circuits contained both dynamic and static circuits. The hydraulic actuators were also used to build pressure for static tests or to accumulate pressure and instantaneously release high pressure for the dynamic tests. A programmable controller was used to control the circuits. This device had characteristics that overcame the limitations of previous designs. Those characteristics included:

(a) The testing device was of vertical configuration. The developed biaxial tester consisted of four actuators, which were orientated at 90° to each other. Four cylinders operated independently and the center point was always maintained at the home position without movement.
(b) Depending on the objective, uniaxial tension and compression tests, biaxial tension and compression tests, static and dynamic biaxial tests under the equal biaxial stress of bars or plates were possible by exchanging chucks only.
(c) Tests under unequal biaxial stress (load ratio of 1:1 to 1:4), static and dynamic biaxial tests under combined stress, dynamic biaxial shearing tests and other loading combinations were possible.

In addition, the machine was equipped with liquid argon cooling and an electrical heating system, which made it possible to conduct a dynamic loading test at controlled temperatures. Aluminum test pieces were tested in the device at testing velocities of 0.02 mm/s for each axis. It was confirmed that the relationship between the load and the strain was proportional for the biaxial test up to $\varepsilon = 1.7\%$ as shown in Fig. 6.

Shimamoto et al. have also used their test device to perform dynamic tests for the investigation of crack extension behavior. An aluminum alloy (A7075-T6) cruciform specimen which included a 30 mm long crack at 45° from the center was tested at 1000 mm/s on the device. The failed specimen is presented in Fig. 7 after the dynamic biaxial test. It is evident that the crack extension behavior has an almost bilateral symmetry. The researchers concluded that the device was suitable for both uniaxial and biaxial dynamic tests.

A test machine was designed by Gozzi et al. to study the behavior of high-strength steel under biaxial loading (Gozzi et

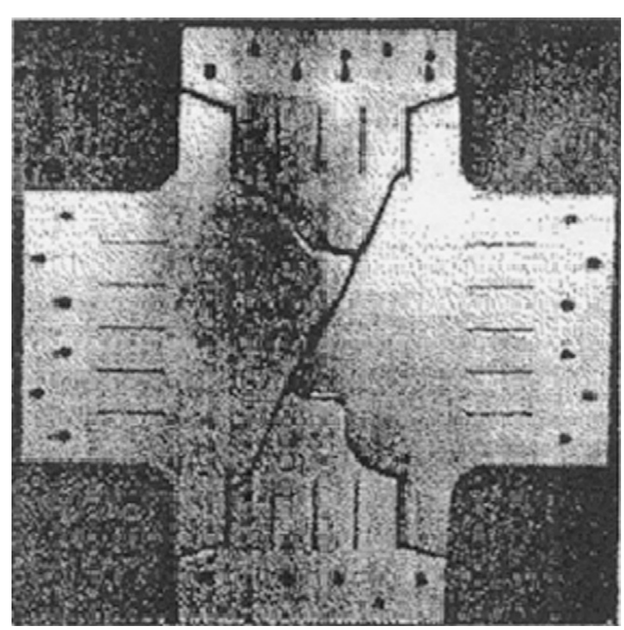

Fig. 7 – Fractured specimen after dynamic biaxial test (Shimamoto et al., 2003).

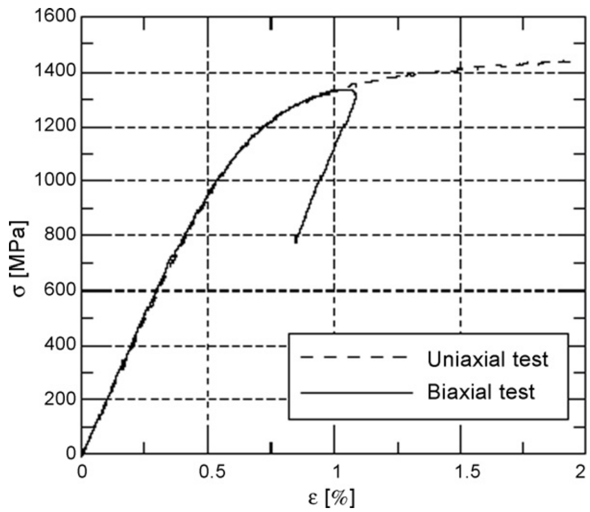

Fig. 8 – Comparison between a uniaxial tensile test and the corresponding initial loading in a biaxial test (Gozzi et al., 2005).

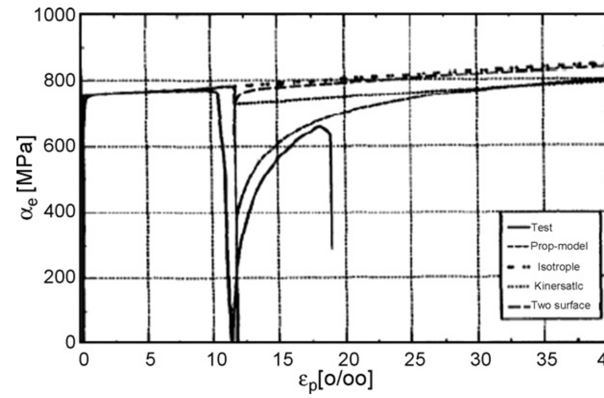

Fig. 9 – Effective stress-effective plastic strain curves for high-strength steel (Granlund and Olsson, 1998).

al., 2005; Gozzi, 2004). It consisted of two actuators mounted perpendicular to each other and four arms hinged at the lower end of the device. The two-actuator concept made the rig self-aligning. The drawback with using the hinged arm setup was that the grips moved along an arc profile. The actuators were controlled by an Instron control unit that could control the two actuators independently. All tests were performed in load control with constant nominal stress rate of 2.7 MPa/s throughout the test. The results of the biaxial tests were presented as stress points corresponding to equal effective plastic strains in the principle stress plane and effective stress-effective plastic strain curves. Results from uniaxial and biaxial tests were compared as shown in Fig. 8. From this data, it can be concluded that the stress in the biaxial specimen during initial loading can be determined with an accuracy corresponding to a uniaxial test.

Granlund studied the effects of a bending force on a cruciform specimen during biaxial testing and found that when the bending force introduced on the specimen was very small it could be considered negligible (Granlund, 1995; Granlund and Olsson, 1998). These researchers designed lateral support plates in order to prevent out-of-plane buckling and thus provide for compression tests. The support plates were clamped around the specimen and the clamping force was measured allowing for the friction losses to be accounted for. Special attention was devoted to design the cross-shape specimen in order to allow the stress in the gauge area to be determined from external load.

Two different steel grades, one high-strength with characteristic yield strength of 690 MPa and one mild structural steel with characteristic yield strength of 275 MPa was tested. The results showed that the initial yield criterion falls between the von Mises and Tresca criteria which complied with many earlier observations. The subsequent yield criteria were characterized by a pronounced Bauschinger effect and more gradual transition into plastic state in subsequent loading opposite to preloading for both steel grades. A new constitutive model, as shown in Fig. 9, was proposed that accounts for the gradual change in the plastic modulus in subsequent loading.

Vegter and van den Boogaard (2006) carried out extensive research on biaxial stress states in sheet metal and proposed an isotropic plane stress yield function based on interpolation by second order Bezier curves. The parameters of the model were derived by mechanical testing. It was demonstrated that the sensitivity of the forming limit diagram (FLD) to small changes in the yield locus could also be used to determine some of the material parameters by inverse analysis. The FLD prediction for an AlMgSi alloy using various yield criteria and comparison with experiment is shown in Fig. 10.

Naumenko and Atkins (2006) performed biaxial tensile tests on pre-cracked high-strength low-hardening aluminum specimens. The focus of their research was on determining the crack tip opening geometry when parameters such as the specimen geometry, specimen size and biaxiality ratio were varied. The researchers concluded that there is a need for too many variables to describe the constraint-dependent crack extension properly. However they demonstrated that the

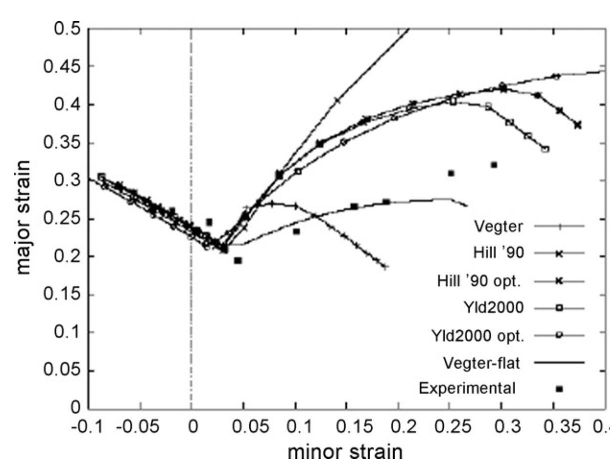

Fig. 10 – FLD predictions for the AlMgSi alloy at 90° to the rolling direction using various yield criteria and comparison with experiment (Vegter and van den Boogaard, 2006).

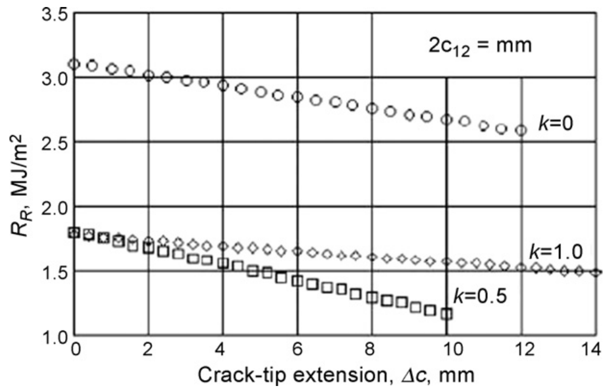

Fig. 11 – Effects of load biaxiality on R-curves expressed in terms of energy dissipation rate R in cruciform specimens (Naumenko and Atkins, 2006).

effect of biaxiality loading on the crack extension resistance, R is unexpectedly strong as shown in Fig. 11.

3.3. *Link mechanism attachments for biaxial testing machines*

In an attempt to reduce the cost associated with building stand-alone test machines, attachments have been designed for existing machines such as tensile and compression testers for the purpose of biaxial testing. The most common biaxial test setup is that of converting a standard tensile machine. This is typically achieved by adding an extra actuator to the system such as the addition of a horizontal hydraulic ram to a vertical tensile test machine. The tensile tester is then used to apply the vertical load and this removable attachment can be used to apply the horizontal load. One such device which was designed by Hoferlin et al. (2000). It consisted of a standard tensile test machine with a removable hydraulic actuator attached. Both the vertical and horizontal loading directions contained load cells and an alignment fixture. The horizontal fixture was mounted on low-friction bearings to ensure that the horizontal structure remained aligned with the center of the specimen during the test. A biaxial test device was developed at the Fraunhofer Institute in Germany by converting a compression tester by a series of linkages (Fraunhofer, 2005). This setup developed is presented in Fig. 12.

This system operated by using four links attached to the cross-head of the compression tester. As the cross-head moved in a downward direction these links converted the movement into horizontal motion in two different directions. This motion was used to apply the force to the cruciform specimen as shown in Fig. 12. As in most cases, a load cell was used in each direction to measure the forces and a camera was used to measure specimen elongation. Mohr and Mulalo (2004) have used a compression testing machine to test honeycomb structures under multi-axial loading. This universal biaxial testing device (UBTD) was used to apply combinations of large compressive and shear displacements to the boundaries of a honeycomb specimen. A further method of transforming a tensile test machine into a biaxial test machine is by the use of links. This method was developed by Ferron and Makinde

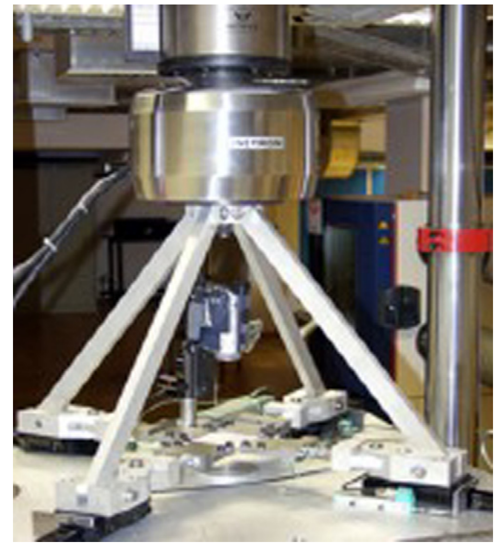

Fig. 12 – Biaxial linkage for compression test machine (Fraunhofer, 2005).

(1988). By using eight links it was possible to convert the vertical movement of the cross-head into directional movement of the grippers. This link mechanism is presented in Fig. 13.

After mounting the specimen on the device, the complete system was attached to the testing machine by means of heads H1 and H2 and tested in tension. During the experiment, the displacement of the vertical frame, made up of the four arms, Av assured a decrease in distance between the connecting parts C1 and C2, which in turn produced an adequate displacement of the horizontal frame made up of the four arms Ah. Thus, the loading system assured an increase in the distance between the two heads H3 and H4. With this configuration, the increase in the distance between H3 and H4 was equal to the distance between H1 and H2. The specimen, fixed to the four

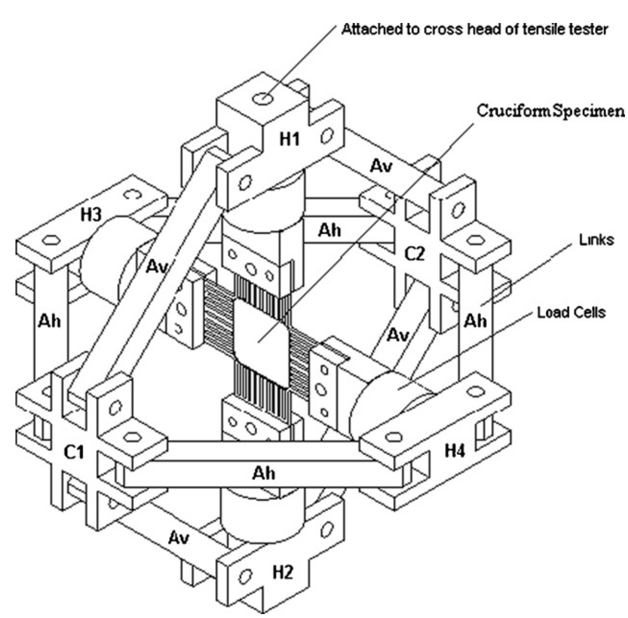

Fig. 13 – Pantograph mechanism for tensile test machine (Ferron and Makinde, 1988).

heads H1, H2, H3 and H4 by means of gripping plates, was subject to an equi-biaxial deformation. When a tensile load was applied to the two heads H1 and H2, the vertical arms were subjected to a tensile load while the horizontal arms were under a state of compression. It follows that the equi-biaxiality of the specimen deformation is true under the assumption of negligible elastic deformation of the mechanism.

The load on the specimen was measured by two load cells, which were positioned on the heads H1 and H4. This system was also used by Terriault et al. (2003) to test various alloys at different temperatures. One of the main differences with this apparatus was that the device was used on a compression-testing machine. Here, a compression force was applied to the heads C1 and C2, which applied the same movement to the grippers as in the previous setup. The pantograph apparatus converted a compression load applied on the two cross-shaped membranes to a biaxial tensile load via the arrangement of eight articulated arms. The strain was measured by the use of a video extensometer. In this study the objective was to examine whether or not the onset of phase transformations could be described by the von Mises criterion. To reach this goal, isothermal Ti–Ni alloy cruciform sample testing was performed at different temperatures. During the high-temperature experiments, it was observed that reduction of the thickness of the specimen legs caused the specimen to fracture outside the gauge section. Therefore, minimum plastic deformation was observed in the gauge section of the specimens resulting in the creation of incomplete stress strain curves. Makinde et al. (1992b) has developed a biaxial extensometer for measuring strain in cruciform specimens. The extensometer allowed for both control and measurement of strains along two mutually orthogonal directions. Strain measurement in one direction was completely independent of the other. Tests were performed using this extensometer on sheet metal and it was found to be in excellent agreement with standard method of measuring low to medium strains.

4. Specimen design

One of the most challenging aspects of a biaxial testing system is test specimen design. Test specimens can vary from cruciform types to cylindrical tubes as used in the bulge test. To perform a biaxial test on sheet metal, a cross-shaped specimen is typically used. The design of the cruciform specimen is the main difficulty that restricts application for the cruciform biaxial tensile test (Yong et al., 2002). Although specimens of the cruciform type have been investigated quite extensively no standard geometry exists (Lin et al., 1993; Lin and Ding, 1995). The lack of standard specimen geometry makes it difficult to compare test results from different laboratories (Makinde et al., 1992a). Different biaxial tests have been performed in parallel to finite element simulation in an attempt to achieve an optimum specimen design. FEA and other simulation models in sheet metal forming in the automotive industry have proven to be beneficial to reduce tool costs in the design stage and for optimizing current processes (Vegter and van den Boogaard, 2006).

Depending on the specific theory, which is used to describe the material behavior, several variables, e.g. tensile strength,

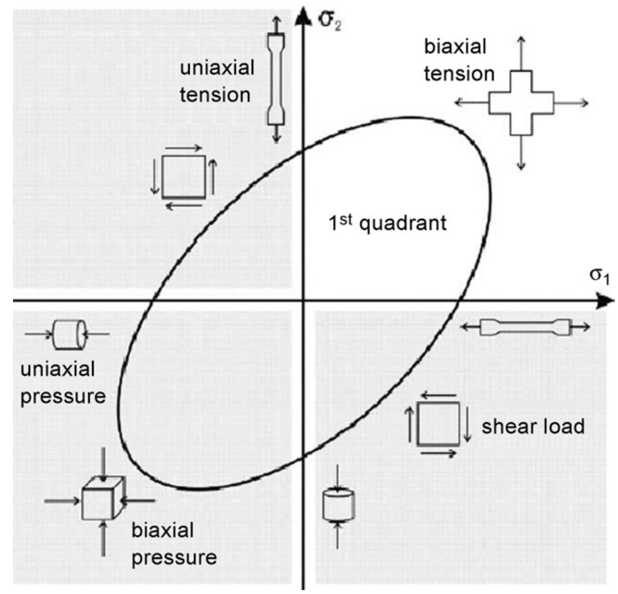

Fig. 14 – Stresses on specimens (Geiger et al., 2005).

anisotropy, yield locus, etc can be taken into account for modeling sheet metal forming. In comparison with parameters that are determined in uniaxial experiments, e.g. uniaxial tensile tests, the yield locus defines a starting point of plastification as a function of the biaxial stress condition (Geiger et al., 2005). The typical force system that acts on the specimen during the test is presented in Fig. 14. A large range of materials other than metals have being examined using the cruciform specimens. These include cellular tissue and composite materials (Brody and Pandit, 2002; Waldman et al., 2002).

In designing a specimen, it is of great importance to have the majority of deformation at the center section of the specimen and to avoid stress concentrations in other regions of the specimen (Demmerle and Boehler, 1993). Deformation capacity of sheet metal under uniaxial tension is much less than that under biaxial tension. Rupture consistently occurs on the arms of the specimen (Yong et al., 2002). There have been a number of methods employed to prevent this in a cross-shaped specimens. The three main methods are the (i) cut type, (ii) reduced section type and (iii) strip and slot type as proposed by Ohtake et al. (1999) and shown in Fig. 15. The cut type uses large radii at the corner sections of the specimen to cause an increase in the deformation at the center section of

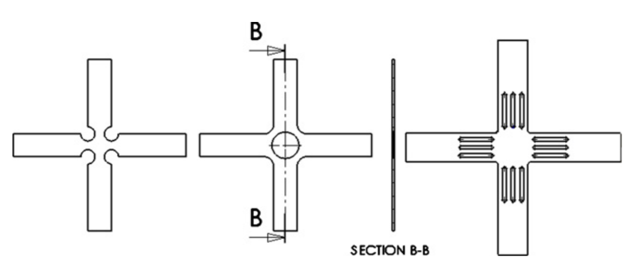

Fig. 15 – Proposed geometry for cruciform type specimen (Ohtake et al., 1999).

the specimen. From the cross-section of the reduced section, presented in Fig. 15, the specimen is reduced in thickness to increase the deformation at the center. The strips used in the strip and slot-type specimen reduce the effect of load sharing on the arms. These slits made in each arm, were found to be very effective in causing uniform strain distribution within the gauge section, allowing the biaxial stress components in the gauge section to be easily identified without assuming the effective cross-sectional area (Kuwabara et al., 1998). These slots are also used to distribute the applied load evenly to the gauge section and also uncouple the two loading axes by allowing more flexibility for the specimen to deform in the two directions (Lin et al., 1993; Donne et al., 2000). This was also shown in a method of gripping the standard square specimens (Waldman and Lee, 2002; Waldman et al., 2002).

In an attempt to investigate the influence of parameters such as: (i) the rounding radius at the intersection of two arms, (ii) the thickness of the biaxial loaded test zone in relation to the thickness of the arms and (iii) the geometry of the test zone on the aforementioned requirements, finite element simulations have been used. Afterwards, these numerical results are normally compared with experimental results obtained from biaxial tests on selected cruciform geometries (Smits et al., 2004).

One of the methods developed to overcome the problem of specimen failure outside the gauge area is to reduce the thickness of the gauge section. Welsh (Welsh and Adams, 2002) carried out a study on optimum design of cruciform specimens and biaxial testing of different laminate types. In an attempt to design an optimum specimen it was discovered that the legs in each direction affected each other. Because cruciform-shaped specimens have two intersecting loading directions, the possibility of load sharing between adjacent loading arms exists. That is, it is possible that all of the applied load in one direction may not be directed into the gauge section, leading to inaccurate stress level predictions in the biaxially loaded gauge section. To concentrate deformation on the gauge section it was reduced in thickness. The specimen designed is presented in Fig. 16.

From this study it was concluded that significant improvements were achieved by altering the geometry of the cruciform specimens to determine the effect on the measured ultimate strength. One such improvement was noted by the occurrence of specimen failure within the gauge section. This provided further evidence that the desired biaxial stress states were achieved at failure using the thickness-tapered cruciform specimen geometry incorporating a 6.35 mm (0.250 in) radius loading leg fillet and a small square gauge section. These results, combined with the fact that a complete biaxial failure envelope was generated in $\sigma_1 - \sigma_2$ stress space using a single specimen geometry, has led the authors to believe that further investigation into the use of thickness-tapered cruciform specimens to determine the biaxial strength of composites materials is justified.

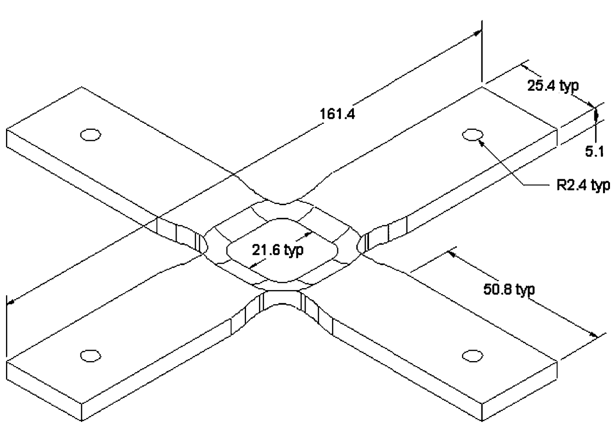

Fig. 16 – Reduced center section specimen (Welsh and Adams, 2002).

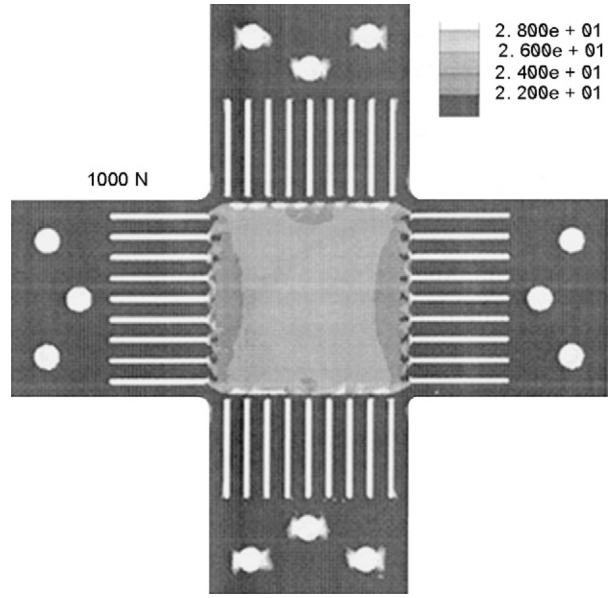

Fig. 17 – FE analysis of cruciform specimen (Terriault et al., 2003).

Terriault et al. (2003) used a cruciform Ti–Ni sample with a reduced section at the central part for biaxial testing at different temperatures. This reduced section ensured that a constant stress field was obtained in the gauge area. The researchers attempted to determine if the onset of a phase transformation could be described by the von Mises criteria when the alloy was subjected to biaxial loading at temperatures above and below the transformation temperature. It was concluded that the von Mises criteria could be used to predict the behavior of the material below the transformation. However, above the transformation, there was no conclusive evidence to show that this criteria was suitable for the deformation behavior. By performing a finite element analysis of the specimen stress fields were identified for the cruciform specimen for various loading conditions. A stress of approximately 25 MPa was recorded at the specimen center as shown in Fig. 17 when an arbitrary load of 1000 N was applied to the specimen in one direction.

Geiger et al. (2005) optimized biaxial test specimen design using FEA. The novel specimen used is shown in Fig. 18. The overall diameter of the specimen was 230 mm with arm widths of 30 mm at 90° to each other.

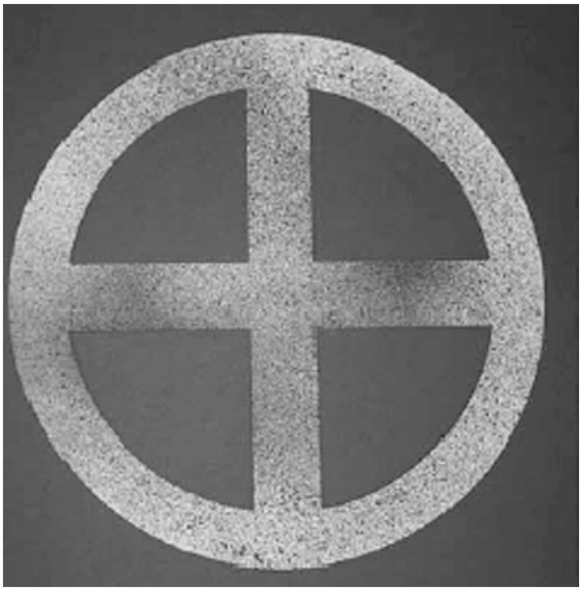

Fig. 18 – Specimen designed by Geiger et al. (2005).

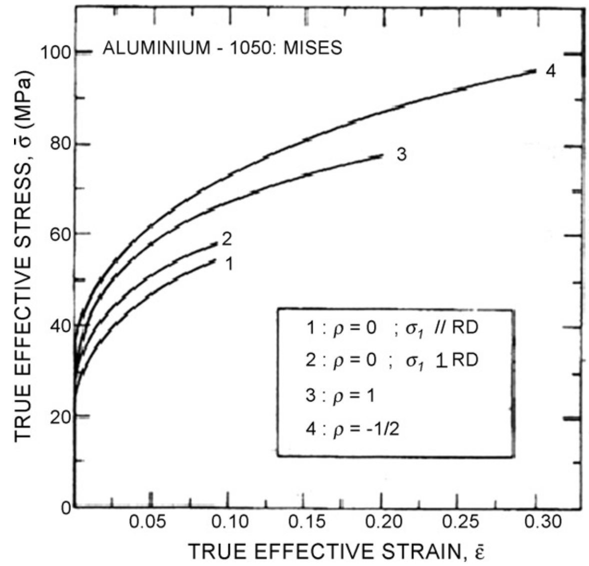

Fig. 20 – von Mises stress–strain curves for biaxial tensile test (Ferron and Makinde, 1988).

The authors made various design changes to the specimen at the intersection area of the legs and to the legs themselves. These changes are shown in the FEA plots in Fig. 19. The authors conclude that the FE modeling enhanced the specimen geometry so that the stresses within the specimen were concentrated in the center.

Ferron and Makinde (1988) have designed a specimen that contained a series of slits in the specimen arms. The specimen geometry resulted in a uniform stress field over a large part of the area where the arm overlapped. Important recommendations from this study were:

- Slots should be cut along the arms of the specimen in order to ensure transversal flexibility and thus eliminate the constraints imposed on the deformation of the gauge section by the lateral stiffness of the arms, thereby allowing for an unrestricted deformation of the gauge part.
- The center section of the specimen should be thinned down so as to essentially localize the deformation within the square gauge region.

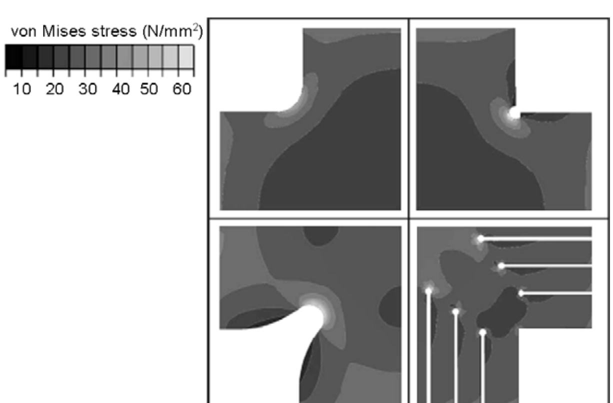

Fig. 19 – FEA stress distributions of various specimen geometries (Geiger et al., 2005).

This specimen was manufactured using annealed aluminum and tested biaxially. An example of the results obtained with the researchers biaxial testing device and specimen is presented in Fig. 20. It is evident that the data obtained under conditions of plane strain are much lower than that expected from uniaxial testing.

Other optimum specimen design studies carried out by Makinde et al. (1992a) were to reduce the effects of specimen geometry on test results. These researchers undertook a study of factors that may influence the stress strain distributions and the failure limit strains in the specimens. Two specimens were designed for small and large strains. Again, the main objective with the design was to achieve uniform stresses and strains within the gauge section. The traditional method of changing one variable at a time may not lead to an optimum design because of the interactions of two or more variables. Both statistical design and FE analysis programs were used to study the specimen geometry variables.

The results from the FEA and the statistical analysis led to the optimum geometrical parameters for some metal alloys. From this study, the stress and strain distributions were found to be concentrated almost totally within the gauge section of the specimen. This optimum specimen developed by Makinde et al. (1992a) is presented in Fig. 21. Work is still progressing on the design of optimum geometry for large strain studies.

Boehler et al. (1994) carried out a study on experimental investigations on anisotropic sheet metals, such as composite plates and rolled sheet metals. For this experiment a new cruciform specimen was designed. Generally, when employing an optimization method to solve a problem, it is necessary to have a well-defined criterion. In the case of cruciform specimen optimization, the criterion for the assessment of the specimen design must take into consideration the following three requirements:

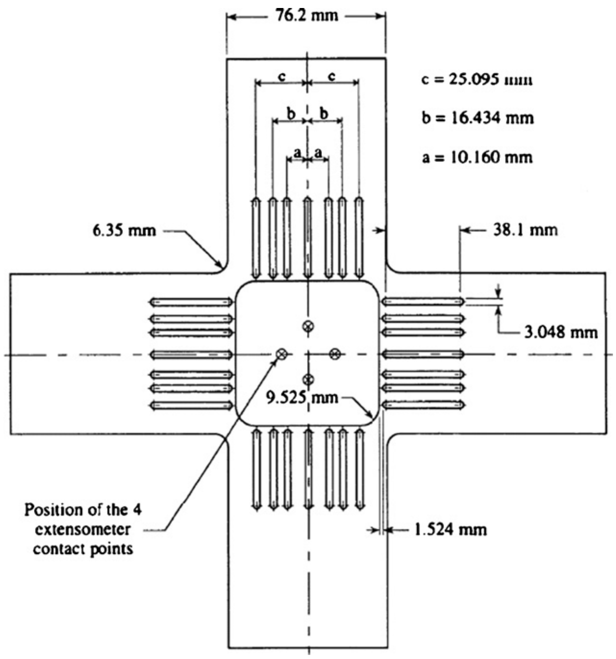

Fig. 21 – Cruciform specimen with reduced center section and slots (Makinde et al., 1992a).

i. Homogeneous stress and strain distributions exist within the test section.
ii. The stress values in the test region are identical to the nominal stress values, which are obtained by dividing each of the two applied loads through the corresponding cross-sections, i.e. area A (Fig. 22). This is very important for the identification of constitutive laws.
iii. The highest stress level can be observed in the test section and it is there, where initial yielding occurs. No stress concentration occurs outside the area.

These researchers used data generated by both experiment and a finite element program in an attempt to reach an optimum specimen design. Results from this research and from other optimum specimen studies by the same authors (Demmerle and Boehler, 1993) found that the optimum number of slots to have in the legs of the specimens was seven. Furthermore, high-stress concentrations were evident at the intersections of the legs.

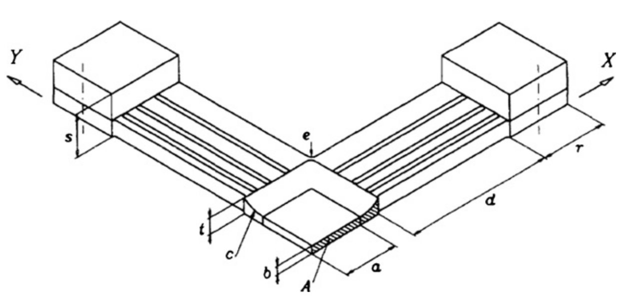

Fig. 22 – Boehler specimen with reduced center section and slots (Boehler et al., 1994).

5. Conclusion

Components of mechanical equipment under load are regularly subjected to multi-axial states of stress. In addition most sheet metal forming is carried out under biaxial stress states and not uniaxial tension. However the stress–strain formability parameters obtained by uniaxial tensile tests have traditionally been applied to deformation induced under plane strain or balanced biaxial stress states. The developing literature, however, has shown that this assumption is not correct. For forming conditions, in-plane biaxial testing of cruciform specimens is crucial for deriving mechanical properties used in design and life prediction. Many attempts have been made to standardize or design a valid biaxial test for flat specimens that would avoid premature material failure at the re-entrant corners and give a large region of uniform strain at the specimen center. This has been achieved with varying levels of success by some researchers as described in this paper. Some researchers have introduced radii between adjacent arms, which reduced stress concentration in the corner sections. Other improvements involved the reduction of the thickness of the gauge section. This caused the stress to be concentrated on the gauge section of the specimen, which in turn caused the gauge section to experience plastic deformation. This method was used in various studies of cruciform specimens and was found to be very effective. Other improvements were the addition of slits to the arms of the specimen. This was done to distribute the load more evenly to the gauge section and also to reduce load sharing between the arms.

As more research was conducted on cruciform specimens, it was found that using combinations of all three methods was very effective.

Various test devices have been designed and manufactured to accommodate cruciform specimens. A key requirement with these test devices is accurate strain measurement. A number of previous researchers have used strain gauges mounted on the specimen while others have used non-contact methods such as camera systems. While an array of strain gauges gives a series of points that can be used to validate a material model and to establish the biaxial strain field in the test region, this technique has limitations. Many of the designed specimens contain holes or slots, therefore, placing a physical limitation on the proximity of the strain gauges to these features. Accurate strain measurement permits the calculation of specimen test area stresses under various loading conditions. It is generally agreed that a non-contact method of strain measurement incorporated in an automatic data acquisition and control system is preferred for biaxial testing. A multitude of configurations for biaxial tensile test machines exist from stand-alone machines to attachments fitted to existing testing machines. There are many advantages and disadvantages associated with each type. Attachments, which are placed on the tensile tester, are more economic and easier to build. The main disadvantage is that, with these attachments only one type of biaxial test can be performed. For example, with the attachments, the ratio between the movement in the X direction and the Y direction are the same, i.e. $\rho = \varepsilon_1/\varepsilon_2 = 1$. If a biaxial test is required in which the ratio of X to Y was 2:1, the links in the device require changing, which is time consuming and often prohibitively expensive. For a stand-alone biaxial testing device, this could be achieved quite easily by changing the ratio or speeds of the motors or hydraulic pumps running the machine. With this type of machine many different biaxial tests could be performed at different ratios and loading combinations in the X and Y direction. The main disadvantage with stand-alone machines is that they are very costly to purchase or build.

In summary, much research is required in the area of biaxial testing for sheet metal. No standard geometry exists for biaxial specimens that could be used for particular material groups. Finite element modeling is a powerful tool that can be used for the optimization of the specimen design. In terms of biaxial test devices, the huge advances made in recent years in the areas of instrumentation and control systems, auger well for the design of automatic, accurate and flexible biaxial test systems.

REFERENCES

Altan, T., 2003. Advanced methods of simulation in tube hydroforming – research progress and case studies, Proceedings of the THF Conference, Stuttgart, October 27/28, p.111.

Boehler, J.P., Demmerle, S., Koss, S., 1994. A new direct biaxail testing machine for anisotropic materials. Exp. Mech. 34, 1–9.

Brody, S., Pandit, A., 2002. Characterisation of the micro-architecture of heart valves. In: Scholar. University of Galway.

DeGarmo, E., Kohser, R., Black, J.T., 1997. Materials and Processes in Manufacturing, 8th ed. Prentice Hall, USA, p. 1259.

Demmerle, S., Boehler, J.P., 1993. Optimal design of biaxial tensile cruciform specimens. J. Mech. Phys. Solids 41 (1), 143–181.

Donne, C., Trautmann, K.H., Amstutz, H., 2000. Cruciform specimen for in plane biaxial fracture deformation and fatigue testing. In: Multiaxial Fatigue and Deformation, pp. 405–422.

Ferron, G., Makinde, A., 1988. Design and development of a biaxial strength testing device. J. Test. Evaluat. 16, 253–256.

Fraunhofer, 2005. Dynamic material testing (http://www.emi.fraunhofer.de).

Geiger, M., Hubnatter, W., Merklein, M., 2005. Specimen for a novel concept of the biaxial tension test. Mater. Process. Technol. (167), 177–183.

Gozzi, J., 2004. Plastic Behavior of Steel. Department of Civil and Environmental Engineering, Lulea University of Technology, Sweden, p. 126.

Gozzi, J., Olsson, A., Lagerqvist, O., 2005. Experimental investigation of the behavior of extra high strength steel. Exp. Mech., 533–540.

Granlund, J., 1995. Biaxial testing of structural steel with cross shaped specimens. In: Nordic Steel Construction Conference, Malmo, Sweden.

Granlund, J., Olsson, A., 1998. Modelling of the plastic behavior of structural steel based on biaxial testing. J. Construct. Steel Res. 46 (1-3), 404–405.

Green, D.E., et al., 2004. Experimental investigation of the biaxial behaviour of an aluminum sheet. Int. J. Plasticity 20 (8-9), 1677–1706.

Groover, P., 2002. Fundamentals of Modern Manufacturing, 2nd ed. John Wilet & Sons, Inc, USA, p. 1008.

Hoferlin, E., et al., 2000. The design of a biaxial tensile test and its use for the validation of crystallographic yield loci. Model. Simulat. Mater. Sci. 8, 423–433.

Johnston, W.M., Pollock, D.W., Dawicke, D.S., 2002, Biaxial testing of 2195 aluminum lithium alloy using cruciform specimens. NASA Report No./CR2002-211942.

Jones, C., 2001. Biaxail testing of polymer composites. Mater. World 9 (11), 19–21.

Jones, C., 2005. Biaxail testing of polymer composites. Mater. World 9 (11), 19–21.

Jones, C., Green, R., 2001. Pulled in different directions. Mater. World, 19–21.

Keefe, A.C., Carman, G.P., Jardine, P., 1998. Torsional behavior of shape memory alloys. Smart Struct. Mater. 3324, 58–67.

Klaus, W., Gerlach, J., 1998. Biaxial Experimental Approach to Characterize Formability of Steel Sheet Metals. Society of Automotive Engineers, pp. 69–75.

Kuwabara, T., Ikeda, 2002a. S. Plain-strain tension test of steel sheet using servo-controlled biaxial tensile testing machine. Proceedings of 5th ESAFORM Conference, Krakow, April, pp. 499–502.

Kuwabara, T., Ikeda, S., 2002b. Measurement and analysis of work hardening of sheet metals under plane strain tension. J. Iron Steel 88 (6), 334–339.

Kuwabara, T., Ikeda, S., Kuroda, K., 1998. Measurement and analysis of differential work hardening in cold rolled steel sheet under biaxial tension. J. Mater. Process. Technol. 80–81, 517–523.

Li, D., Ghosh, A., 2004. Biaxial warm forming behaviour of aluminum sheet alloys. J. Mater. Process. Technol. 145, 281–293.

Lin, S.B., Ding, J.L., 1995. Experimental study of the plastic yielding of rolled sheet metals with the cruciform plate specimen. Int. J. Plasticity 11 (5), 583–604.

Lin, S.B., Ding, J.L., Zbib, H.M., 1993. Characterization of yield surfaces using balanced biaxial tests of cruciform plate specimens. Scripta Metall. Mater. 28 (5), 617–622.

Makinde, A., Thibodeau, L., Neale, K.W., 1992a. Development of a apparatus for biaxial testing for cruciform specimens. Exp. Mech. 32, 138–144.

Makinde, A., et al., 1992b. Design of a biaxial extensometer for measuring strains in cruciform specimens. Exp. Mech. 32, 132–137.

Martin, P.J., et al., 2005. Biaxial characterisation of materials for thermoforming and blow moulding. Miner. Min. 34 (5–6), 276–282.

Mohr, D., Mulalo, D., 2004. Experimental Investigation on the plasticity of hexagonal aluminum honycomb under multiaxial loading. J. Appl. Mech. 71, 375–385.

Naumenko, V.P., Atkins, A.G., 2006. Engineering assessment of ductile tearing in uniaxial and biaxial tension. Int. J. Fatigue 28, 494–503.

Ohtake, Y., Rokugawa, S., Masumoto, H., 1999. Geometry determination of cruciform type specimen and biaxial tensile test of C/C composites. Key Eng. Mater. 3, 151–154.

Pun, A., 2003. Multiaxial fatigue models the real world. Mach. Design 75 (9), 26–28.

Samir, A., et al., 2006. Service-type creep-fatigue experiments with cruciform specimens and modelling of deformation. Int. J. fatigue 28 (5–6), 643–651.

Schodel, M., Zerbst, U., Donne, C., 2006. Application of the European flaw assessment procedure SINTAP to thin wall structures subjected to biaxial and mixed mode loadings. Eng. Fract. Mech. 73, 626–642.

Shimamoto, A., Shimomura, T., Nam, J., 2003. The development of a servo dynamic loading device. Key Eng. Mater. 243–244, 99–107.

Smits, A., et al., 2004. Study of the usability of various cruciform geometries for biaxial testing of fiber reinforced composites. Proceedings of the 21st International Congress of

Theoretical and Applied Mechanics Warsaw, Poland, August 15–21.
Soni, S.R., Balan, M., Cross, C., 2003. Response characteristics of composites under combined bending and in-plane loading. SAMPE 2003.
Terriault, P., Settouane, K., Brailovski, V., 2003. Biaxial testing at different temperatures of cruciform TI–NI samples. In: Shape Memory and Superelastic Technologies, California.
Vegter, H., van den Boogaard, A.H., 2006. A plane stress yield function for anisotropic sheet material by interpolation of biaxial stress states. Int. J. Plasticity 22, 557–580.
Vlassak, J.J., Nix, W.D., 1992. A new bulge test technique of Young's modulus and Poisson's ratio of thin films. J. Mater. Res. 7 (12), 3242–3249.
Waldman, S.D., Lee, J.M., 2002. Boundary conditions during biaxial testing of planar connective tissues. Part 1: Dynamic behaviour. J. Mater. Sci.: Mater. Med. 13 (10), 933–938.
Waldman, S.D., Sacks, M.S., Lee, J.M., 2002. Boundary conditions during biaxial testing of planar connective tissues. Part 2 Fiber orientation. J. Mater. Sci. 21, 1215–1221.
Welsh, J.S., Adams, D.F., 2002. An experimental investigation of the biaxial strength of IM6/3501-6 carbon/epoxy cross-ply laminates using cruciform specimens. Composites: Part A 33 (6), 829–839.
Xiang-Dong, W., Wan, M., Xian-Bin, Z., 2005. Biaxial tensile testing of cruciform specimen under complex loading. J. Mater. Process. Technol. 168, 181–183.
Yong, Y., et al., 2002. Design of a cruciform biaxial tensile specimen for limit strain analysis by FEM. J. Mater. Process. Technol. 123, 67–79.