Determining the state of stress in the narrow section of Arcan test specimens, by the FEM method

N A Danila1,2, I Blanari1,2 and P D Barsanescu1,*
1 ”Gheorghe Asachi” Technical University of Iasi, Mechanical Engineering Department, 47 Mangeron Blvd, Iasi, Romania
2 National Institute of R&D for Technical Physics, NDT Department, Iasi, Romania
E-mail: paulbarsanescu@yahoo.com

Abstract. Mohr-Coulomb failure criterion is used to establish the failure conditions under a compound state of stress. According to this criterion, materials failure is produced to a certain combination of normal and shear stresses. Arcan type tests are an easy way to study the specimens behavior in pure and mixed mode (tensile & shear) respectively. The fixture allows an ARCAN sample to be rotated at 15° increments from 0° to 90° to produce different amounts of mode-mixt during loading; with 0° being pure tension/compression loading to 90° being pure shear loading. The Arcan method, like the Iosipescu method, uses specimens with a predetermined breaking section. A condition for material testing is that the stress in the narrow section to be as uniform as possible. This depends on the shape and depth of the notch. Starting from apriori knowledge about Iosipescu specimen, the modelling will be carried in FEM software to optimize the shape of the specimen, in order to obtain more uniform stress in cross section. A FEM is performed for Iosipescu specimen, designed for pure shear, when it is mounted in Arcan device, so it is need to be studied for some complex states of stress. The studied material is aluminum alloy type 7075, used in aerospace industry. This analysis is necessary before the tests are carried out, in order to adopt an appropriate form of the specimens.

1. Introduction

Aluminum alloy has recently returned with a high level of use in the aerospace and automotive industries. Magnesium alloys with a low percentage of Mg or Al-Li have the advantage of being lighter and less flammable. From this reason, the failure of structural components from aluminum alloys, submitted to complex axial stresses is more studied nowadays.

The Iosipescu type test is used on a wider scale for pure shear, and it is also standardized to be applied to different materials. The Iosipescu shear test proved to be applicable for the accurate determination of the strength and stiffness characteristics of the materials, requiring a rigid and precisely constructed device, as well as special gauge marks for this test. The first recognition of the applicability of the Iosipescu test was in 1986 [1] when it was compared with the existing tests. Research included the premature failure study due to stress concentrators, non-alignment and torsion of samples, and uneven distribution of loading. There were performed studies on the sensitivity of the notches according to the depth, the radius and the angle of the notch, as well as the loading points, recommending the increase of the sample sizes [1].

In 1993, the American Society for Testing and Materials (ASTM) officially recognized the Iosipescu shear test as the standard protocol (ASTM D5379-93) [1]. The development and use of the
Iosipescu method has achieved a number of advances which, however, remain under-represented compared to other testing methods. Although the Iosipescu specimen is considered an ideal test piece for shear testing \[1, 2\], Arcan has published papers describing a new shear test and operating principle \[1, 2\]. In the pure shear zone, the specimen must have such shape so that the isostatics shall intersect at 45° angle. The Arcan device is simple, inexpensive and it can be mounted on a common machine for the tension test. The paper presents the proposed Arcan device for tests based on the Iosipescu specimen, studying the behavior of the aluminum alloy to mixtures, using the finite element analysis in the ANSYS software. For pure shear tests, using Iosipescu specimens, accurate results can be obtained with both devices (Arcan and Iosipescu, respectively). Starting from this observation, in the paper is analyzed the possibility to use Iosipescu specimens mounted on Arcan device, that represents a novelty. The state of stress in the fracture section of the sample has been determined by Finite Elements Analysis (FEA). Quite uniform stresses have been obtained for pure shear and tension with shear respectively (with different ratios normal stress / shear stress), but in tension the normal stress has an important gradient in the immediate vicinity of stress concentrators. Ponomarev \[1\] showed that in such cases the shape of stress-strain diagram is changed, but the yield stress and ultimate stress (which matters for the experimental analysis) practically does not change. Thus, the use of Iosipescu specimens shall improve the Arcan method.

2. Theoretical principle

The vast majority of the structural elements and machine parts are subjected to different compound stresses (i.e. they are in a spatial or plane state of stress). Testing of materials under multiaxial states of stress can be very difficult and expensive because very complex testing machines and even specimens with complicated shapes are required. Consequently, it is not possible to do these tests for any material and any state of stress. In such cases, the strength of materials calculation uses the limit state theories (strength or yield theories, respectively). These theories (or criteria) establish relationships between principal stresses \(\sigma_1, \sigma_2, \sigma_3\) and a parameter chosen for the characterization of the limit state (\(\sigma_1\) is maximum stress, \(\sigma_3\) the minimum stress, and \(\sigma_2\) is the intermediate stress). An equivalent stress \(\sigma_{eq}\) is usually established, which allows to compare a triaxial or a biaxial or state of stress with the uniaxial tension. As tensile limit stress, the yield stress (for ductile materials) or ultimate stress (for brittle materials) can be used. After establishing the equivalent stress, a simple calculation for tension is made \(\sigma_{eq} \leq \sigma_a\), where \(\sigma_a\) is the allowable stress or design stress. If equivalent stress exceeds certain limits, even in a very small volume around a point in the body, the material around this point fail because the yield or even fracture of material can be initiated. Unfortunately, there is no a universal limit state theory: some theories are dedicated to ductile materials, others to brittle materials and others only for certain materials or groups of materials. Among these, the Mohr-Coulomb theory probably has the broadest field of application. It can be applied for both brittle and ductile materials \[1\]. The Mohr-Coulomb theory postulates that materials fail when a certain combination of normal stress \(\sigma\) and shear stress \(\tau\) is produced in a section of the body (figure 1).

The equivalent stress predicted with this theory is

\[
\sigma_{eq} = \sigma_1 - K\sigma_3
\]

where

\[
K = \frac{\sigma_{LT}}{\sigma_{LC}}
\]

Coefficient \(K\) characterizes the different behavior of material obtained for tension and compression test, respectively. The limit state of stress for tension is \(\sigma_{LT}\) and respectively \(\sigma_{LC}\) for
compression. For ductile materials, tests show that

\[ \sigma_{LT} \approx |\sigma_{LC}| \]  

(3)

**Figure 1.** According to Mohr-Coulomb criterion, materials fail when a certain combination of stresses $\sigma$ and $\tau$ is produced in a section of the body (a); the Mohr’s circle (b).

In this case $K = 1$ and the Mohr-Coulomb criterion degenerates into the Tresca criterion (or the theory of maximum shear stress)

\[ \sigma_{eq} = \sigma_1 - \sigma_3 \]  

(4)

The Mohr-Coulomb criterion consider only the maximum and minimum principal stresses ($\sigma_1$ and $\sigma_3$ respectively) and neglects the influence of intermediate stress $\sigma_2$. Because there are many states of stress in which $\sigma_2$ has a small influence [8], the Mohr-Coulomb criterion can be used both for biaxial and triaxial states of stress.

In order to test the samples under the complex states of stress, the requirements are:
1. Testing machines or devices as simple as possible must be used;
2. Samples should have of simple form which can be easily made;
3. In the breaking section, the state of stress must be as homogeneous as possible and isostatics must be straight lines;
4. The states of stress in the loading points must not interfere with the state of stress in the breaking section;
5. The ratio of principal stresses in the breaking section must remain constant throughout the test.

The above conditions are not easy to accomplish.

3. **Device for test**

To test the Mohr-Coulomb theory, testing of materials under combined tension with shear is required. Using the Arcan device, these tests can easily be performed.

Arcan device use the butterfly specimen fixed on two steel half-disks with two asymmetrical cuts. The shape of the specimen concentrates the stress towards its center, where is cross section. The Arcan test has been developed to collect data regarding the strength of materials at tensile and shear in different biaxial state of stress. The specimen has been simulated by FEM at different loading angles $0^\circ - 30^\circ - 45^\circ - 60^\circ - 90^\circ$. Using the Arcan device, the samples can tested under different states of stress.

The butterfly-type specimens used for Arcan test have the following disadvantages:
1. They are large and use more material;
2. The connection at the bottom of the notch is made by large radius and for this reason no precise results can be obtained for the shear test.

Of course, the Arcan specimen represents a compromise between the specimens for tension and shear test. However, these two specimens have very different shapes and a compromise is difficult to achieve. The tension and shear test respectively can be done with specific specimens and methods. However, using the Arcan device, a single type of specimen is intended to be tested under different
states of stress produced by uniaxial tension, pure shear and different combinations of tension and shear. To remove the deficiencies above, this paper proposes to use the specimens intended for the pure shear test (Iosipescu method) also for Arcan test. The use of the Iosipescu test for the Arcan test has the following advantages:

1. The Iosipescu specimen is small compared to the Arcan specimen;
2. Using Iosipescu specimen the most precise results will be obtained for pure shear test.

Figure 2. Arcan device.

The question is whether the Iosipescu specimen can provide satisfactory results for the tension test. Ponamarev et al. [8] have shown that the use of specimens with stress concentrators for the tension test could modify significantly the stress-strain diagram and could change the character of fracture (ductile / brittle). Nevertheless, the ultimate stress does not change significantly compared to that obtained with the standardized samples for tension test. Based on this observation, one might assume that the Iosipescu specimen could also provide good results for the Arcan test. In order to verify this assumption, a finite element analysis was done for one Iosipescu specimen mounted in the Arcan device, under different cases of loading.

4. FEM sample for simulation
FEM procedure for 2D model is presented in figure 3, using ANSYS software.

Figure 3. The diagram of FEM.

The loading and unloading conditions are: the force applied is 10kN, and from Figure 2 we can see the two loading directions (load on \( OX \) axis, \( \alpha = 0^\circ \), the tension test is performed and there was only the normal stress \( \sigma \); loading on \( OY \) axis, \( \alpha = 90^\circ \), the tension test is performed and there is only shear stress \( \tau \)). For an angle comprised between \( 0^\circ \) to \( 90^\circ \) different biaxial states of stress can be obtained. The Iosipescu test piece has the shape and dimensions presented in figure 4 according to ASTM [3]. Loading conditions are presented in figure 5, on half of specimen is applied a vertical force with a magnitude of 10 kN. The specimen is fixed at half geometry at all direction for prevented body motion. The FE model expected to represent more realistic way for load transfer to the Arcan specimens. The thermal variation is also neglected.

The FEM model mesh contained 29231 nodes and 9568 elements for entire geometry. The results of FEM simulation are presented below, for different angles. In table 1, the elastic properties of the material chosen for the simulation are presented.

Figure 7 presents the variation of normal stress at \( \alpha = 0^\circ \) loading. Figure 8 presents the variation of shear stress at \( \alpha = 90^\circ \) loading.
Table 1. Physical and mechanical features of the simulated material

| ρ (kg/m³) | E (GPa) | μ | σ_{adm} (MPa) | σ_{r} (MPa) |
|-----------|---------|---|---------------|-------------|
| 2770      | 7.1     | 0.33 | 494           | 528         |

For pure shear, the shear stress distribution known in literature was obtained. For tension, the normal stress shows sudden increases in the immediate vicinity of stress concentrators. These results were expected. Under different compound states of stress quite uniform stresses have been obtained. These results could not be anticipated because the Iosipescu sample is used currently only for pure shear and not under a compound state of stress. For static tests a state of stress as uniform as possible is necessary. Using FEM, it has proved that the Arcan method accuracy can be increased when Iosipescu specimens are used.

Figure 6. The simulation of Iosipescu specimen: a) the meshing type; b) the narrow zone.

Figure 7. Variation of σ in the fracture section at α=0° loading.

Figure 8. Variation of τ in the fracture section at α=90° loading.

5. Conclusions
The Arcan device behavior at mixed stressed have been studied, showing the significance of Iosipescu specimen and the reliability of the Arcan test result. Following FEM simulation of Iosipescu specimen tested on Arcan device, the variation of stresses in the fracture section can be describes as:

- At shear loading, the distribution of tangential stresses τ is the same as at the Iosipescu device;
- At tensile test, the variance of normal stress σ is uniform across most part of the section, but marks two significant peaks in the area of the stress concentrators (from about 175 MPa in the central area to 570 MPa in the vicinity of the stress concentrators);
- Normal equivalent von Mises stresses are fairly uniform in failure section.

![Figure 9. Von Mises stress: a) $\alpha = 30^\circ$; b) $\alpha = 45^\circ$, c) $\alpha = 60^\circ$.](image)

Using FEM it was shown as the Iosipescu specimen can be mounted on Arcan device and so one important requirement of static testing of materials, concerning the stress uniformity in the fracture section, may be accomplished.

Further research will use various geometries of samples, such as: a sample with a constant section for the traction test; for shear test, an Iosipescu type sample may be used. For a combined state of stress, the angle of the Iosipescu sample (equal to 45 degrees in the standardized form) can be modified in order to ensure that the maximum value of the stress is found on the central part of the sample and not near to the ends of the narrow section.

It is going to check through tests whether the tensile ultimate stress for aluminum alloys is the same, whether the specimen has or not stress concentrators. Thus the Arcan test method can be used to determine the mechanical properties of materials such as shear strength and shear modulus.

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