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Von mises stress distribution along the cruciform specimen under biaxial loading: geometric variation effect

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Abstract. The aim of this work is to optimize the geometry of the cruciform specimen required for in-plane biaxial testing where the failure has to occur in the central gauge region. The specimen has three different zones with three different thickness, i.e., (i) along the arm, (ii) Milled region and (iii) along the central gauge region. The geometric variables in the specimen are the radii at four different locations in the geometry (i) central gauge (ii) radius of the slots milled along the arm, corner radius at (iii) Milled region and (iv) at the intersection of arms. The Taguchi method was realized for the design of experiments considering these four factors varied at three level. However, the effect of the variation in the thickness was studied independently. During which the thickness at the central region was maintained constant to 0.7mm, whereas the thickness at the other two positions were varied from 3 mm to 3.5mm and 1 to 1.5 mm respectively. In the first set of experiments the Von Mises stress was maximum at the gauge section along with a portion of it also being appearing along the milled region on the arm of the specimen. However, for the second set of experiments the maximum stress occurred along the gauge region for the three geometries. Later, Taguchi analysis indicated the radius of the slots milled along the arm is the prime statistically influencing factor and the radius at the interface of the arm section is the second statistically influencing factor. Whereas the other two radii are found to be statistically non-influencing factor when considered individually. However, a strong interaction has been observed between all the four parameters.

Introduction

The sheet metal operation is a process where in the materials being processed are generally subjected to most complex stress state. Customarily, these process are basically designed based on the uniaxial test data which is found to be insufficient. Because the test data resulting from the regular tensile test would be able to determine the properties solitary along the direction of the load being applied which, possibly will not be suitable to use for these processing as they experience a multi-directional stress state [1]. Subsequently, the biaxial testing of materials have become a subject of great significance in order to establish the material characteristics under such loading conditions [2]. Typically, a thin-walled tubular specimen or a bar of circular cross-section which is subjected to either an axial or a torsional loading conditions are regularly used for the material evaluation for biaxial state of stress. However, these geometries experience few challenges such as (i) the limitation of producing a pure thin cylinder, (ii) eliminating the edge effect and (iii) these test are not appropriate for materials which are produced by rolling [3-4]. As a result the flat cruciform specimen subjected to the in-plane biaxial loading is gaining importance.

However, the key for the success of these samples is the cruciform specimen design. Typically, one can identify three precincts in such geometries which are sensitive. These areas are (1) the specimen arms section, (2) The center region of the geometry, and (3) the area about the transition zone between two adjacent arms. While designing such geometry it is significant to confirm that a huge extent of the deformation occur at the central region of the specimen, with no stress concentrations zones in the other regions, principally while the large strains are essential [5]. In the recent past, different cruciform shaped specimen geometries made of metallic materials were subjected for analysis either under a quasi-static biaxial pull or under a fatigue loading [6-12]. The international standard ISO 16842: 2014 (E) [13] proposed a cruciform specimen with slots in the arm along with a fillet at the transition zone of the. Nevertheless, owing to a low strain level at the specimen central region, it is challenging to realize either a fracture or necking state at that region. Furthermore, if due to the slots or slits that are made about the arm, strength at may be decreased when compared with the central zone. Thus, creating a possibility of failure being occurring at the slits under a fatigue loading situation making the geometry to be inappropriate for testing under such conditions. Thus, it is not applicable to the biaxial fatigue test. With the intention to get over the above said limitations a reduction of thickness and designing the fillet radius or fillet geometry was suggested. The base geometry was the optimal geometry presented in the study [14] were the effect of the geometric variations were studied. Three geometries were subject for study of which cruciform geometry with round corner at the intersection of arms and tapered along the length was proposed to be optimal. However, it was not presented if the central region is the only place where the maximum stress is occurring or there is a possibility of the same to occur at the interface of the two arms.

The present paper is focused on selecting a suitable geometry from the modified base geometry which could be effectively implemented to understand the biaxial behavior of metallic materials. Taguchi design of experiments was implement to in order to understand the outcome of the geometric variation on the maximum Von Mises stress and its occurrence along the sample. An L9 orthogonal array was used as the factors considered were the geometric radii at four different positions under three levels.

Optimization of the specimen geometry:

A complex stress situation along the central region in a cruciform shape specimen is observed when it is subjected to a biaxial tension. Where a non-uniform direct stress and a shearing stress are observed along the central region of the specimen. Moreover, the arms of the specimen experiences a uniaxial loading and the central region experiences a biaxial loading causing a failure to occur along the arm of the specimen. This failure is due to the fact that under the uniaxial loading the deformation capacity is less when capered to that in a biaxial loading case [15]. Thus the main objective of the optimization is to determine an appropriate specimen geometry which generates a uniform and maximum stress along the center region. The basic geometry for the analysis as mentioned above is the optimal geometry proposed by Mohammed et al [14]. Where in the geometry of the specimen had two circular slots of 1 mm depth along the arm length and a 1.15 mm deep circular slot at the center. These slots were symmetric about the thickness of the specimen which was 3mm and the elementary geometry is represented in fig 1. However, in the present study the radius for the milled region and the curvature R1, R2, R3 and R4 are varied in order to optimize the geometry to produce a uniform maximum stress about the circular milled region and the variation in the radii are presented in table 1. This circular milled region in the specimen geometry is the gauge section for the present study. Moreover, the thickness of the specimen at different sections i.e., the thickness along the arm length and the center milled region are as so altered, later in the study. Two different categories of specimens were observed, the first set which is the case –I had the same the thickness variation as suggested earlier [14]. Whereas for the second category i.e, the case – II the thickness of the overall sample and about the circular slots was increased to 3.5mm 1.5 mm respectively. However, for optimization this variation in thickness is not considered as a parameter for the analysis. Rather than going with all the variations an orthogonal array L9 was used for designing the experiments which is presented in table 2 for both the category.

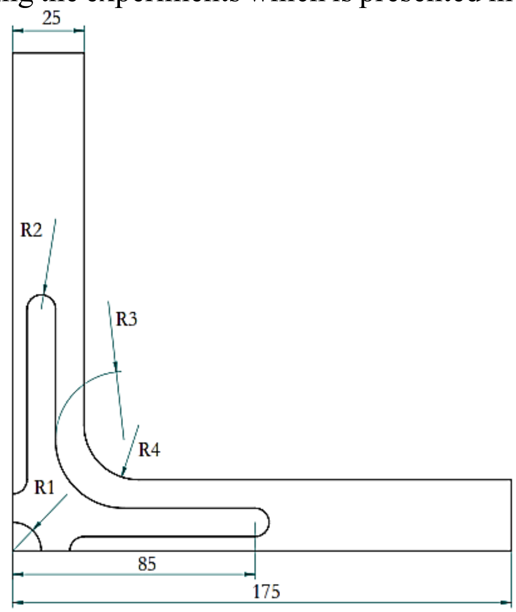

Fig1: Elementary specimen geometry.

Table1: Variations in the radii

	1	2	3
R1	10	12	14
R2	5	6	7
R3	18	20	22
R4	36	38	40

Table2: Design of experiments

Specimen Name	*R1*	*R2*	*R3*	*R4*
CA - I	10	5	18	36
CA - II	10	6	20	38
CA - III	10	7	22	40
CA - IV	12	5	20	40
CA – V	12	6	22	36
CA - VI	12	7	18	38
CA - VII	14	5	22	38
CA - VIII	14	6	18	40
CA - IX	14	7	20	36

Finite Element Analysis:

With the intention of simulating the effect of biaxial stress on the mentioned nine different geometries, ANSYS® a commercially accessible finite element analysis package was implemented as a numerical tool. The material for the specimens was A1050-H14 a ductile aluminium alloy which finds its application in the electrical and chemical industries whose properties are tabulated in table 3. In order to utilize the advantage of geometric symmetricity a quarter geometry was modelled during the analysis and a layered eight nodded linear three-dimensional shell element was selected for discretisation. At each node, the shell element possess six degrees of freedom with three translational and three rotational degree about the nodal coordinates (x, y and z-axis). A biaxial stress ratio of 1:1 was applied along the two perpendicular axes of the arms of the sample and the boundary conditions employed are presented in Figure 2. Where, the two symmetric edges were constrained by symmetricity and a distributed force of 1kN was applied on the arms of the sample.

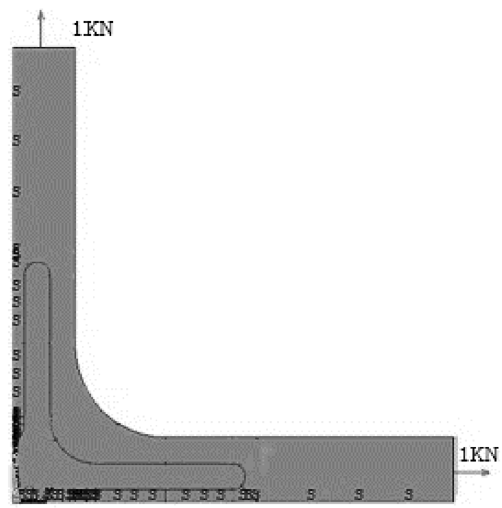

Fig 2: Boundary conditions

Results

The von misses stress dissemination over the nine different geometries under the first category under study is presented in fig 3. And it is clear that, the stress for all the nine geometries is uniform at the gauge section but the existence of maximum stress is at different locations. The maximum Von Mises stress for the geometries CA – I, CA – II, and CA – V, is along the gauge region. However, a small portion of it is also observed along the milled region (i.e., at the slot section) Whereas, for the other specimens the maximum Von Mises stress is either at the milled region or at the interface/intersection of two arms.

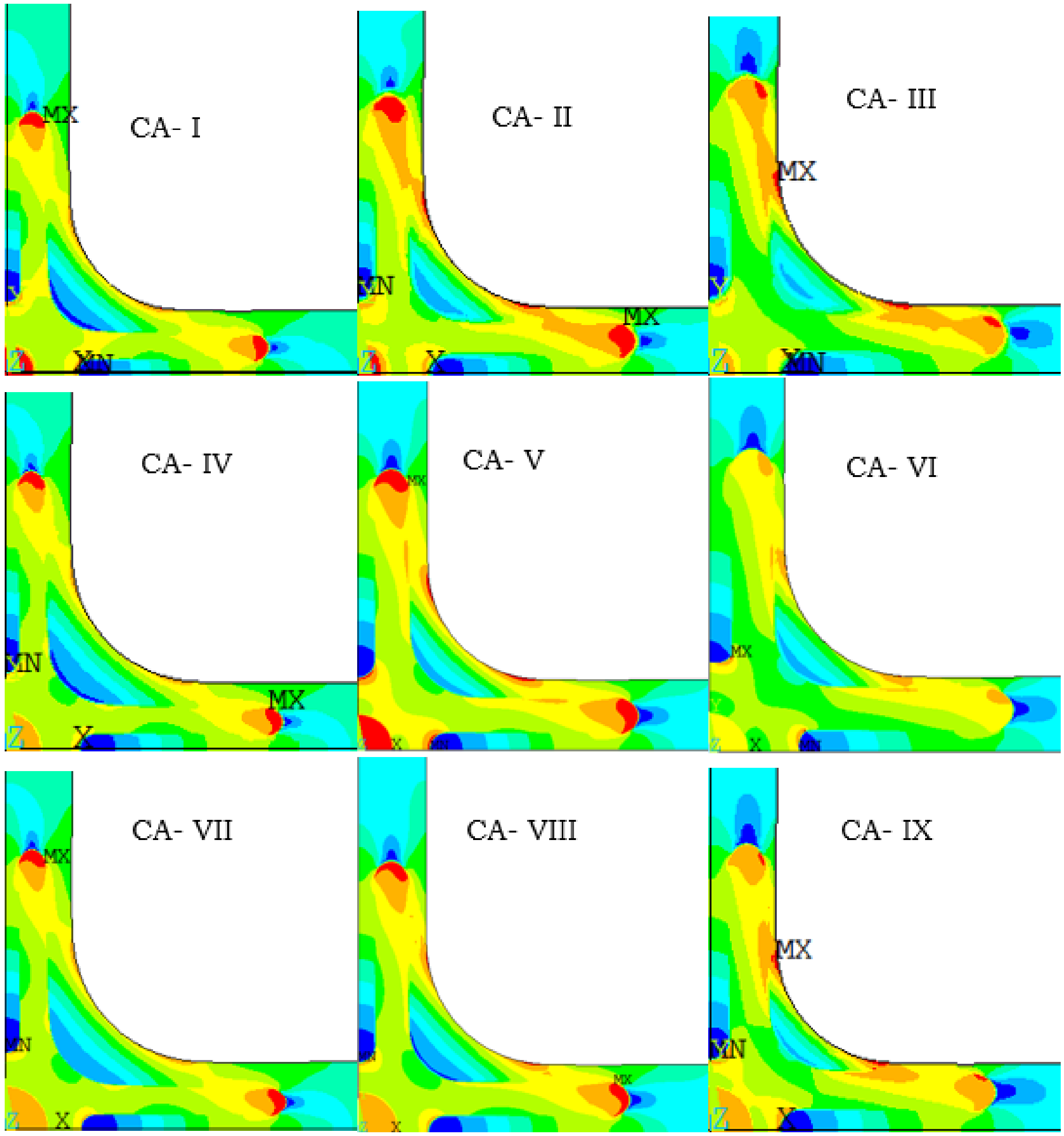

Fig 3: Von Mises Stress distribution on various geometries of first category.

Thus, the thickness of the sample about the milled region were varied as mentioned in the section 2 in order to study the variation of Von Mises stress at the region of interest. Figure 4 signifies the deviation of the Von Mises stress over the nine geometries belonging to the second category. It is clearly evident from the analysis that for all the samples the Von Mises stress was maximum at the central gauge region.

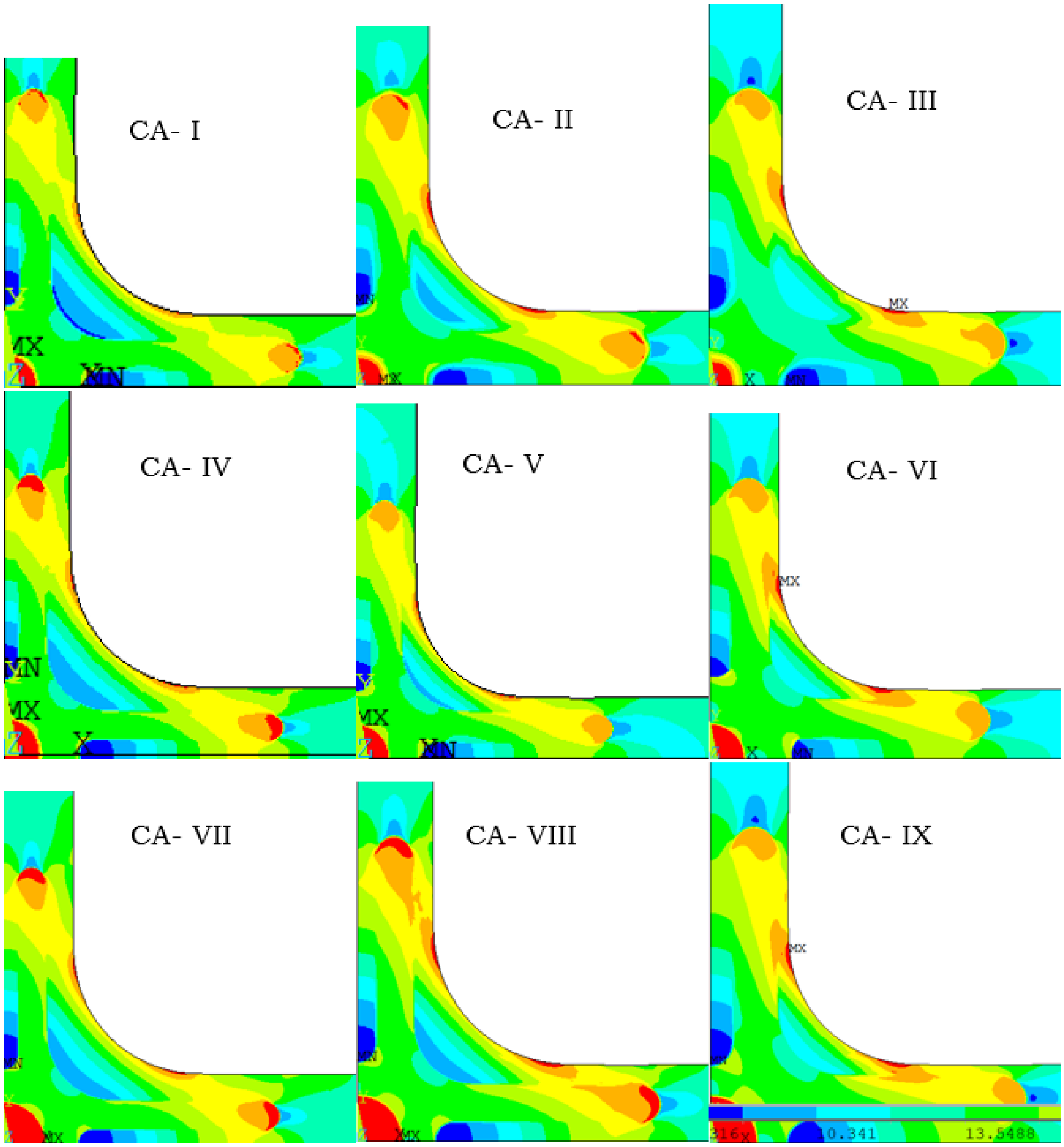

Fig 4: Von Mises Stress distribution on various geometries of Second category.

However, there is a small portion of maximum Von Mises stress even at (i) either the milled region i.e., along the slots or (ii) at the interface region for all the geometries except CA- V. Moreover, to confirm the better geometry the stress distribution along the central region equidistant nodal points along the diagonal and along the arm length were selected as represented fig 5. The path 1 in the fig 5 indicates the selection of the nodal points along the diagonal of the specimen and sequence 2 represents the selection of the nodal points along the arm length.

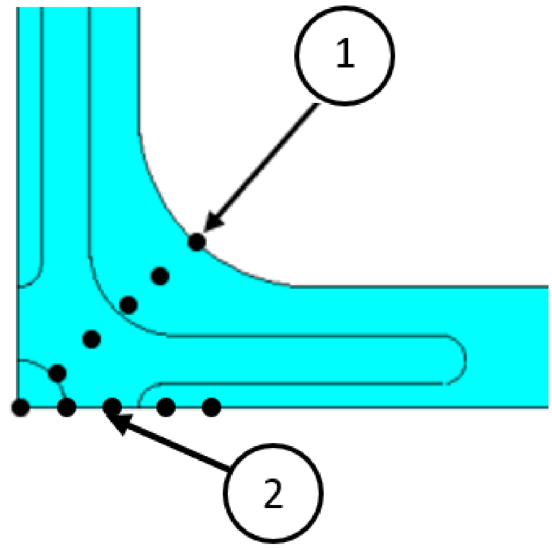

Fig 5: Selection of nodal points along the (1) diagonal and (2) along the length of the sample.

The Von Mises stress distribution was approximately linear for most of the geometries along both the paths consider and the variation is presented in fig 6 and fig 8. However, for the samples with geometries CA I, CA II, CA III the stress distributions is uniform only for about 1 mm or less along the path 1 beyond which the stress decreases. Whereas, for all the other sample geometries the Von Mises stress is uniform until the gauge section. The sample geometry CA IX indicated a high stress value beyond the gauge section and the variation could be seen as a nonlinear with a very low degree of nonlinearity. The fig 8 represents the strain distribution along the diagonal of the sample (i.e., along path 1). A negative strain is observed throughout the path selected with an increasing strain value until the gauge section, beyond which the strain started reducing until 25 mm from the center of the specimen. The stress distribution to be more specific the Von Mises stress along the path 2 is presented in fig 8. Where a similar pattern of stress distribution as that of path 1 is observed. However, the stress uniformity for the samples with geometries CA I, CA II, CA III was linear until 2 mm beyond which it decreased in stepped form. The shear strain distribution along the path 2 is presented in fig 9 and it is clearly evident that the variation in the shear strain with respect to the distance was uniform with a zero strain for all the samples except CA I, CA II and CA III.

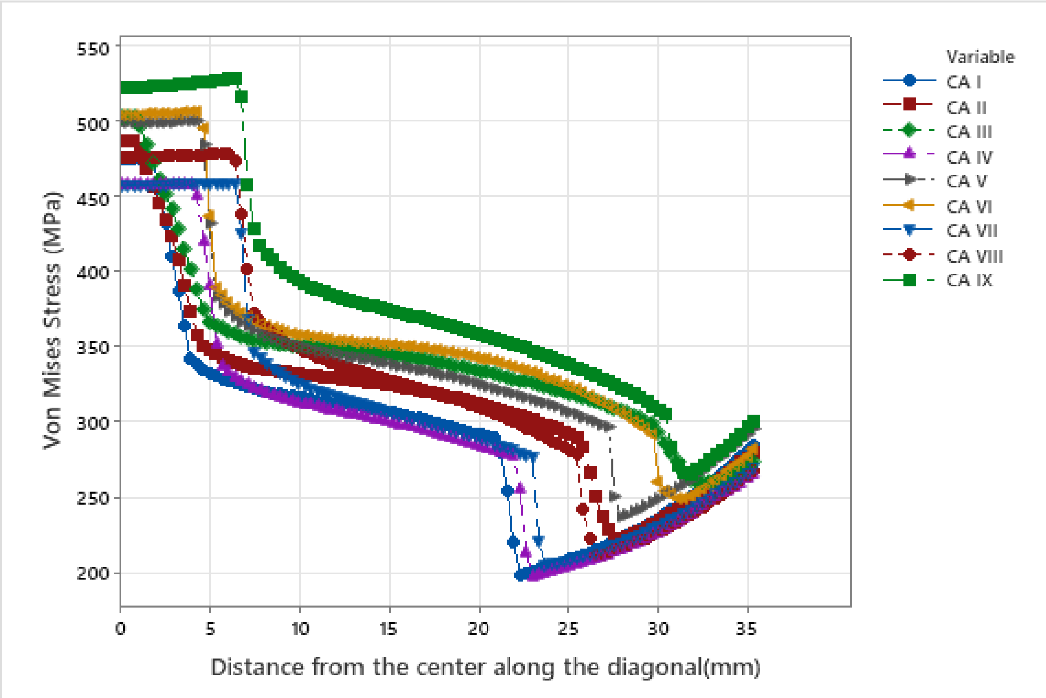

Fig 6: Von Mises Stress distribution along the diagonal of the sample.

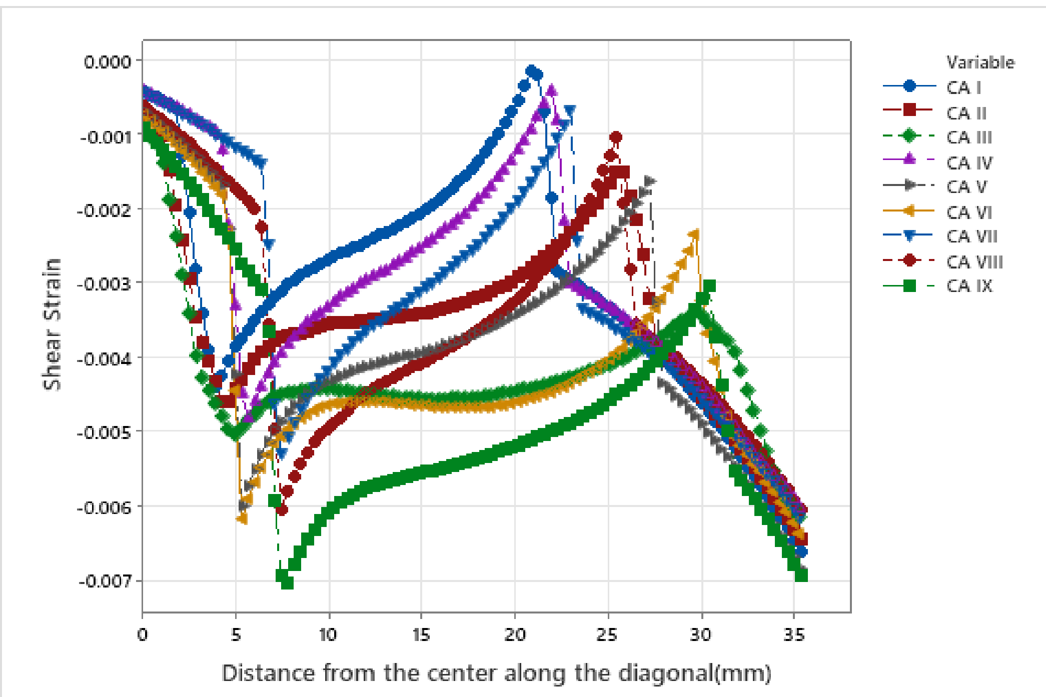

Fig 7: Maximum Shear Strain distribution along the diagonal of the sample.

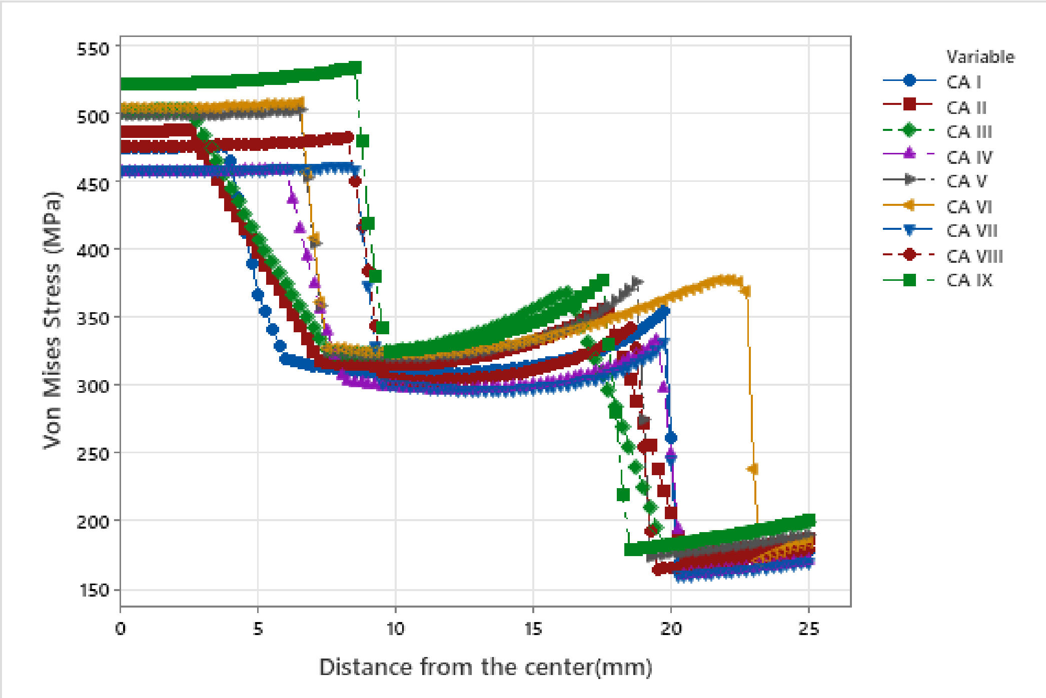

Fig 8: Von Mises Stress distribution along the arm length of the sample.

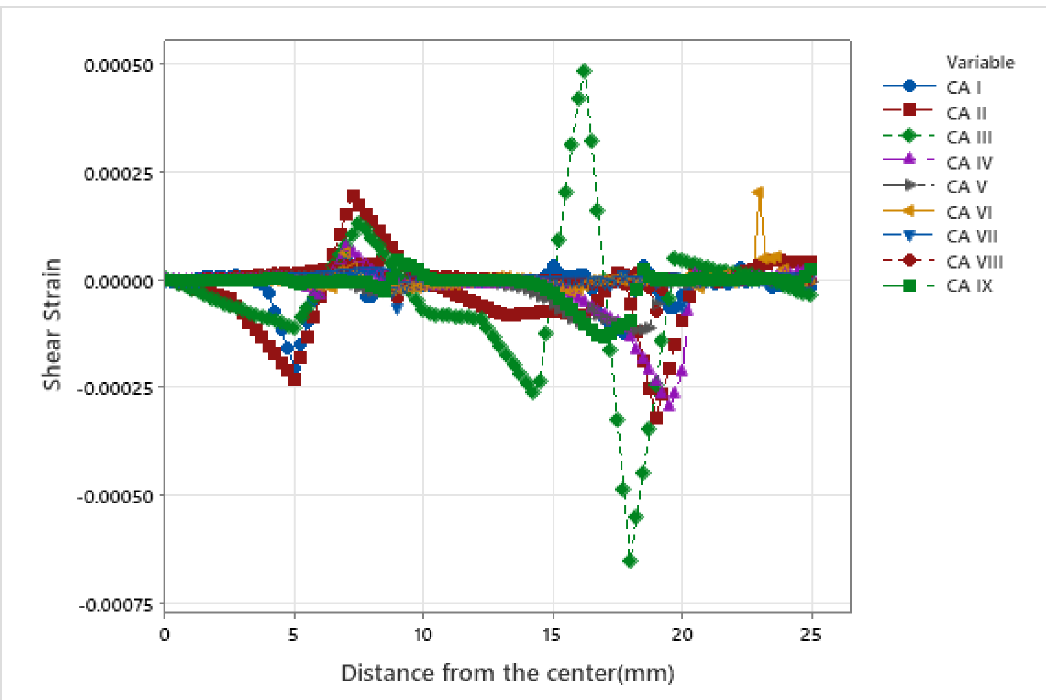

Fig 9: Shear Strain distribution along the arm length of the sample.

Taguchi analysis was carried out to determine the effect of individual variables on the Von Mises stress at the central region, to be more specific at the centre of the specimen. The table 3 and 4 presents the response table with respect to the signal to noise ratio and means. It is clear that the radius of the slot section, R2 has a rank 1 indicating that this variable is most influencing factor and the second being the R4 with rank 2 which is the radius at the interface of the arm section. However, the other two factors i.e., R1 and R3 have a rank of 3 and 4 respectively for the signal

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to noise ratio and rank 4 and 3 respectively in the mean table. The fig 10 represents the main effect plots of means for the maximum Von Mises stress at the centre. It is clear from the figure that the variables R1 and R3 have no significant effect on the occurrence of the maximum Von Mises stress individually as they are approximately linear and are very near to the mean line. However, as mentioned earlier the other variables R2 and R4 have a considerable effect on the occurrence of maximum Von Mises stress. It is also evident that as the radius R2 increases an increase in the Von Mises stress is observed. However, a converse situation is witnessed with respect to the radius R4 i.e., as the radius R4 increases a reduction in Von Mises stress is observed. Furthermore, the optimal variable sequence suggested by the analysis is R1, R2, R3 and R4 being 10, 7, 20 and 36 mm respectively.

Table 3: Response Table for Signal to Noise Ratios (Larger is better)

Level	R1	R2	R3	R4
1	53.77	53.32	53.71	53.95
2	53.74	53.75	53.77	53.68
3	53.71	54.14	53.74	53.59
Delta	0.07	0.83	0.06	0.36
Rank	3	1	4	2

Table 4: Response Table for Means (Larger is better)

Level	R1	R2	R3	R4
1	488.3	463.4	485.1	498.5
2	486.8	487.3	488.7	483.2
3	485.2	509.6	486.6	478.6
Delta	3.1	46.2	3.6	20.0
Rank	4	1	3	2

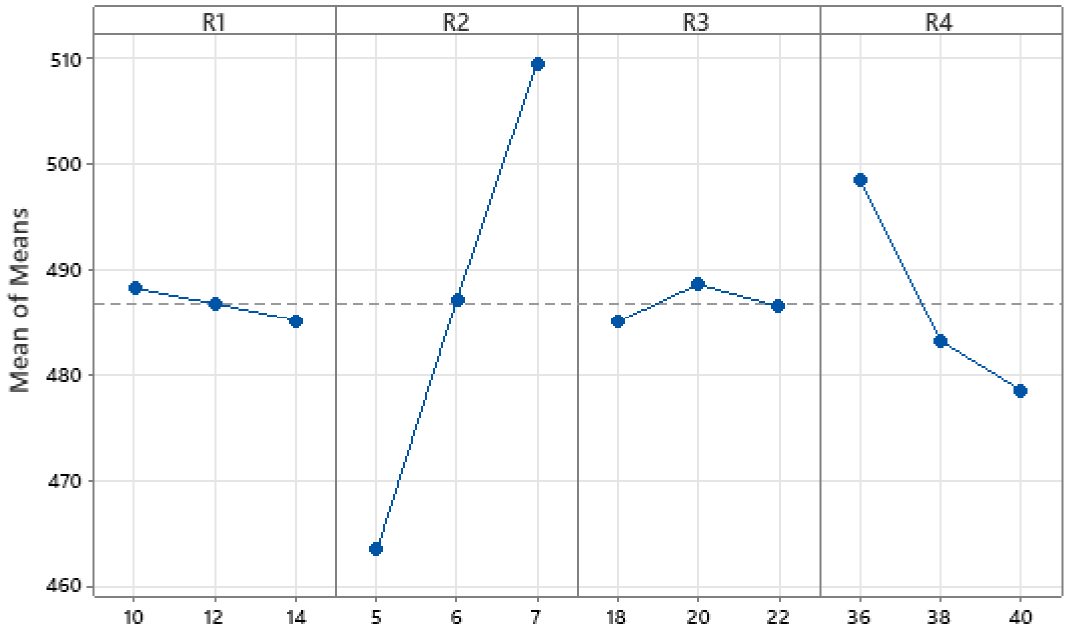

Fig 10: Main effect plot for means.

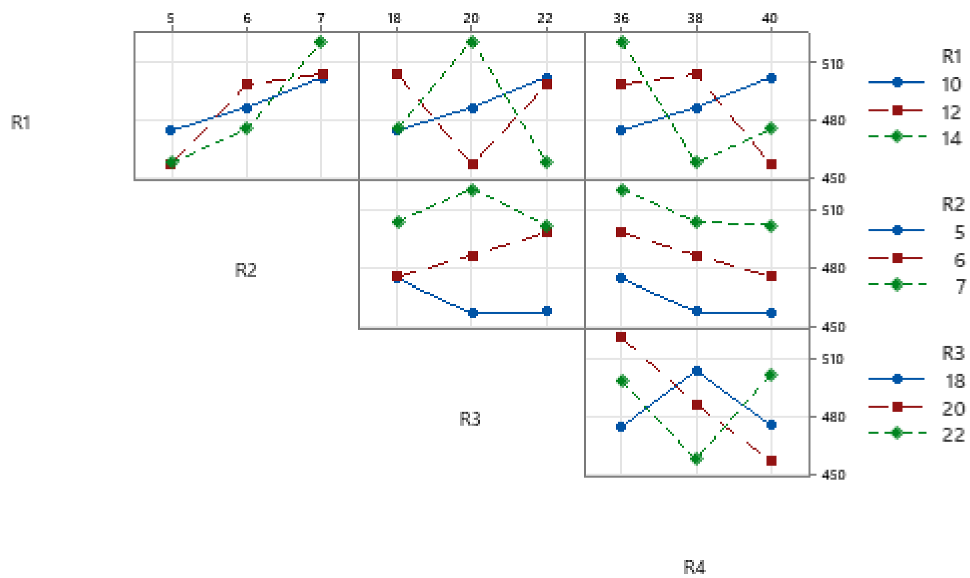

Fig 11: Interaction plot for Von Mises stress.

Nevertheless, the sequence suggested by the analysis is by considering the individual effect which cannot be considered without determining the effect of interactions. The fig 11 represents the interaction plot where a good interaction between all the variables is observed. Yet, a distinctive relation between the main effecting variables i.e., the radius R2 and R4 indicated no interaction.

Conclusions

In the prime aim of the present study was to determine the suitable geometry required for the in-plane biaxial testing of aluminium A1050-H14 material. A basic geometry suggested by Mohammed et al.[14] was selected and the geometric variant in the radius at the gauge section, milled region along the arms and the interception of the arms were varied for the current study. As there were four variables (factors) which were varied at three levels Taguchi design of experiments was implemented to design 9 experimental sequence rather than full experimental sequence. The effect of the thickness was not considered while designing the experiments in the first stage i.e., in case - I rather another set of 9 experiments with same variable sequence was carried out in the second stage in case –II. Later, the following conclusions are drawn from the study.

1. In the case – I, the specimen geometries CA – I, CA – II, and CA – V indicated the occurrence of the maximum Von Mises stress at the gauge zone with a small portion of it is also along the milled region (i.e., at the slot section). While, for the other specimens' occurrence of maximum Von Mises stress was either along the milled region or at the interface/intersection of two arms.
2. In the case – II, for the entire sample geometries range the maximum Von Mises stress occurred at the central gauge region, except the geometries CA- III, CA – VI and CA – IX. In these three geometries the maximum stress has occurred along the interface of the arm yet a portion which is not maximum but almost impending the maximum value is observed at the gauge region.
3. A uniform Von Mises stress distribution was observed in all the geometries of case – II when the elements were selected along the specimen diagonal and along the arm length. Conversely, the shear strain along the diagonal elements indicated an increment in shear strain along the negative direction. While a constant shear strain was observed for elements along the arm length at gauge length except for the geometries CA – I, CA – II and CA – III. For these geometries the strain has changed its orientation from negative to positive.
4. Taguchi analysis indicated that the radius of the slot section, i.e., R2 has a rank 1 indicating itself being a statically most influencing factor and the radius at the interface of the arm section i.e., R4 is the second statically influencing factor. However, the other two factors i.e., R1 and R3 were found to be non-influencing factors when analysed independently. The optimal variable sequence suggested by the analysis is R1, R2, R3 and R4 being 10, 7, 20 and 36 mm respectively. However, a strong interaction between all the factors with each other except R2 and R4 is observed.

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