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Orientation Effects of Stress Concentrators on the Material Deformation Behaviour during Tensile Testing of Thin AISI 316 Stainless Steel Strips

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Abstract: *Present investigation pertains to carry out to experimental work to generate data in order to establish the mode of material deformation and fracture in AISI 316 stainless steel strips of 1.70mm thickness in the presence of elliptical notches at the center of the specimen whose major axis were designed to incline to the tensile axis at an angle of 0^o, $45^o$and $90^o$and the same happens to be the axis of rolling. An elliptical hole of 8.00mm (major axis) with 5.0mm (minor axis) were machined in each specimen so as to correspond to the above angles of 0^o $45^o$and$90^o$and one specimen without any elliptical hole as a notch for comparative analysis of the experimental data. These flat specimens with and without stress concentrators were tested under tension using Hounsfield Tcnsomctcr and the changes in notch geometry have been recorded at various loadings. Further, the visual appearance of the cracks initiation have been continuously observed and recorded. The effect of stress ratio factors and the strain ratio parameters on the mode of fracture on material deformation in and around the stress concentrator has been thoroughly analyzed and it has been established that the crack initiation began either at the inner tips of the minor or the major axis of the elliptical stress concentrator, but, always perpendicular to the direction of loading irrespective of the rolling direction and the orientations of the stress concentrators. However, the changes in the rotation of the major and the minor axis of the elliptical stress concentrators were found to alter, and, this alteration in fact assisted in estimating the strains along the major as well as the minor axis of the stress concentrators. Relation between a plastic strain ratio with respect to the ratio between the major and the minor strains was observed to be of extremely complex nature. The overall observation in the present investigation has indicated that thin strips or sheet specimens containing a single or multiple or a combined type of stress concentrators will create a keen interest in the research approach of the investigators and make them aware of the seriousness of the presence of the stress concentrators and caution them to incorporate any possible design notifications in order to avoid any catastrophic failure (s).*

Keywords: *Stress raiser, Stress concentrator, Tensile testing, notches, Geometry, Fracture, Catastrophic failure, Plastic strain ratio.*

I. Introductin

Advances in the field of fracture mechanics have been worked out by researchers so wonderfully to offset some of the potential dangers which were forced uponthe materials bythe always multiplying rapid technological complexities. Scientists, technologists and materials engineers understanding of how the materials fail and our ability to prevent such failures has increased considerably since the World War - II , much remains to be learnt. However, the existing knowledge of fracture mechanics is not always applied when appropriate. An economy survey conducted in USA estimated that the annual cost of fracture in 1970 was US$ 119 billion either by pulling it apart or by shearing one part over the other. Furthermore, the study estimated that the annual cost could have been reduced by US$35 billion if current technology were applied and that further fracture mechanics research could have reduced this figure by an additional US$ 28 billion[1]. Further advancing beyond this simple concept towards a deeper understanding of fracture phenomena, the subject matter immediately turns out to be extremely complex. Failures caused by tensile loading can be cleavage or grain boundary cracking. The concept of cleavage is straight forward, but, its actual occurrence is complicated. However, higher rates of loading can result in cleavage to occur at temperatures where ductile fracture could have been common. Certain chemical environments can induce cleavage type of fractures in face centered cubic metals such as stainless steels, aluminium and brass, which in normal atmospheres cannot be made to fail at any temperature and any rate of loading. Cracks along the grain boundaries occur for a variety of reasons and they can be caused by brittle network zones denuded of strengthening alloying elements, by stress corrosion attack in certain chemical environments, or at elevated temperatures, by grain boundary sliding and void formation. Shear fractures are equally complex type although they are generally less troublesome because of the fact that the high shear stress necessary to cause separation usually produces sufficient flow to prevent catastrophic fracture. It has been also established that the state of stress controls the occurrence and the mode of fracture. It has been accepted beyond any degree of uncertainty that the presence of cracks, notches and changes in section is unavoidably occurring in almost all engineering structures. Discontinuities of such types have been solely responsible for the catastrophic failures of bridges, tanks, ships and pipelines, all operating within the normally safe range of stresses.Structural discontinuities act as a magnitude of the stress enhancement that can be calculated from the elastic theory or measured with photo elastic or strain gauge techniques.

However, it is not only the increase in stress that causes brittle behavior in normally ductile materials, but, it is the change in the state of stress that is responsible. The qualitative effects of plate thickness, notch sharpness and the crack size have been realized for many years to influence the fracture mode. A geometrical discontinuity in a body as a hole or a notch would result in a non-uniform stress distribution at the vicinity of the discontinuity. At some region near the discontinuity, the stress is expected to be higher than the average stress at distances remote from the discontinuity. Thus, a stress concentration would occur at the discontinuity or stress concentrator. Structural failures are quite often categorized as negligence during design, construction or operation of the structure or the adoption of new design or material, which might produce undesirable results. In the first instance the existing procedures and standards are sufficient to avoid failure, but are not followed by one or more of the parties involved, due to human error, ignorance, negligence or willful misconduct. Poor workmanship, inappropriate or substandard materials, errors in stress analysis and operator errors are some of the examples of where the appropriate technology and experiences are available, but, are not applied. However, the second type of failure is more difficult to prevent. Whenever, an improved design is introduced, there are invariably many factors left behind which the design could not anticipate. It is undoubtedly true that newer materials can offer tremendous advantages but are also the source for many unavoidable potential problems. Therefore, often recommendations are made that a new design or a material must be employed in service if extensive testing and analysis have been carried out. Approaches based on the above can reduce the frequency of failures, but, cannot ensure cent percent elimination because there could have been many factors that would have been overlooked during testing and analysis. There are numerous problem areas in engineering design. Many of them are economic in nature whereas others involve public health and safety. But the closest to the engineer, for which he has the primary responsibility, is the problem area of fracture. While looking for a simple approach to fracture problem, it is clearly understood that there are only two basic ways that a piece of metal can be broken. The same can be separated into two pieces Under this category of failure, brittle fracture of the world war - II Libertyships is a standing example. These ships which were first to have all welded hull that could be fabricated much faster and cheaper than earlier riveted design, but, a significant number of these sustained serious fractures as a result of the design change. It is interesting to acknowledge that all the ships of today are welded and do not fail as sufficient knowledge gained from the analysis of the liberty ships failures have been utilized to build today's ships. Over the past few decades, the field of fracture mechanics has undoubtedly prevented a substantial number of structural failures. One will never know how many lives have been saved or how much property damage has been avoided by applying this technology. However, the fracture mechanics can help the designers to rely on rational analysis rather than on trial and error.

1.1 Fracture Mechanics

Experiments performed by Leonardo da Vinci several centuries earlier provided few clues as to the root cause of fracture. He measured the strength of iron wires and found that the strength of the wire varied invariably with the length. Thus it was implied that the flaws in the material controlled its strength, a longer wire corresponded to a larger sample volume and a higher probability of sampling a region containing a flaw. However, his results were highly qualitative. Griffith established a quantitative relationship between stress and flaw size, in 1920 [2]. He applied stress analysis of an elliptical hole in a plate to an unstable propagation of a crack [3]. Griffith invoked the first law of thermodynamics to formulate a fracture theory based on a simple energy balance. According to his concept a flaw becomes unstable when the strain energy change due to increment of crack length is just sufficient to overcome the resistance to crack growth arising from surface energy, the fracture occurs. However, the Griffith's model quite accurately predicted the relationship between strength and the flaw size in glass specimens. But, the subsequent attempts to apply Griffith's model to metals were unsuccessful as his model assumed that the work of fracture came exclusively from the surface energy term, valid only for ideally brittle materials.

A fracture mechanics group at Naval Research Laboratory (NRL) at U.S.A headed by George Irwin postulated that the energy release rate concept [4], which is related to Griffith's theory, but, is in a form that is more useful for solving engineering problems. It was established by him that the stresses and displacements near the crack tips could be described by a single constant that was related to the energy release rate. This crack tip characterizing parameter came to be known as the stress intensity factor, 'K'. Even though, there were number of successful application of the stress intensity factor (K) and the energy release rate concepts of Irwin to explain various fractures,but, his concept also met with a significant opposition.

Further, in 1960, Paris and his co-workers [5] failed to find a receptive audience for their ideas on applying fracture mechanics principle toa fatigue crack growth. Although Paris et al have provided very convincing experimental and theoretical arguments for their approach, but, the design engineers were not ready to abandon their S-N curves in favour of a more rigorous approach to fatigue design. Paris was unable to publish his results in any technical journal. Finally, the same was published in his University periodical, "The trend in Engineering". Once the fundamentals of linear elastic. fracture mechanics (LEFM) were fairly understood, attention was turned back to crack tip plasticity. LEFM ceases to be valid when significant plastic deformation precedes failures. Irwin's plastic zone correction [6] was the first step in the progress. Wells [7] proposed crack opening displacement concept. In 1968 Rice proposed another parameter. J- integral as the crack tip parameter idealizing the plastic deformation as nonlinear elastic materials [8]. Hutchinson [9] and Rice and Rosengren [10] viewed the J-integral a non-linear elastic stress intensity parameter as well as energy release rate parameter. Rice's work could have been relegated to obscurity had it not been for the active research efforts made by the nuclear power industries in the early 1970s. Due to legitimate concerns for safety, as well as political and public relations active considerations, the nuclear power industry adopted to apply the state - of -art technology in fracture mechanics in design and construction of nuclear power plants. Material toughness characterization is the only one aspect of fracture mechanics. In order to apply fracture mechanics concepts to design, one must have a mathematical relationship between toughness, stress and flaw size.

1.2 Stress Concentration in a plate During Simple Compression containing an Elliptical Hole

An analytical solution for the stress concentration ias available in the event of a tiny elliptical hole in a plate which predicts the maximum stress at the ends of the hole and the same is given by the relationship as is stated below:

$P_{ma}x_{=}P_0\ \{1+2(a/b)\}$-------- (1)

Now analyzing equation (1), it is observed that the stress increases with the ratio of (a/b) and, therefore, a very narrow hole such as a crack ‘normal to the tensile direction will result in a very high stress concentration. This is due to the fact that as (1/b)→0,or in other words ‘b’ cquires values much larger than ‘a’, i.e., b>>a, then the product of 2 and a/b has approached to zero which simply means that the maximum stressthat can now exist when the stress concentrator has almost become extremely slender is expressed by the equation as given underneath:

$P_{max\,=}\ P_0$ ----------------------- (2)

However, as an alternative condition, arises when ‘b’ is simply equal to ‘a’, i.e., b = a, which means that the shape of the stress concentrator has become circular. In this scenario, equation (1) reduces to the following:

$P_{max\,=}\ 3(P_0)$-------------------- (3)

Now analyzing the equation (1) critically, it can be assessed that the stress enhances with the ratio of (a/b), and, therefore, a very narrow hole such as a crack normal to the tensile axis would result in a very high stress concentration.

However, the effect of stress concentrator would be much more pronounced in a brittle material. But, in a ductile material, the plastic deformation would occur when the yield stress is exceeded at the point of the maximum stress. Still, further increase in load would produce a local increase in the strain at the critically stressed region with a little increase in stress. This is because of the fact that strain hardening which will compensate the increase in stress with a little rise in stress values unless otherwise the material is sufficiently ductile, the stress distribution would remain essentially uniform. This simply goes to establish that if a ductile material is loaded statically is not expected to develop the full theoretical stress concentration factor. However, a redistribution of stress will not occur to any extent in a brittle material, and, therefore, a stress concentration of close to the theoretical value will finally approach.

II. Experimental Details

Materials required for the present investigation is the AISI 3 16 stainless steel rolled sheet of 1.7 mm thickness and the same was procured. The chemical analysis of the sheet has been carried out and the various alloying elements that are present in this steel are provided below in terms of weight percentages:

Table I Chemical Composition of AISI 316 Stainless Steel Sheet Used In the Present Investigation

Elements Present	Cr	Ni	Mo	Fe
Weight %	17.0%	12.0%	2.5%	Balance

The equipment used for the present investigation have been Hounsfield Tensometer, drill bits of different diameters ranging from 1.6 mm to 4.0 mm to create elliptical holes to required dimension and the smoothening of the holes has been carried out by using a set of: Jeweler’s file. Dimensional measurements both initial and during the experimentation have been carried out by using digital Vernier calipers. Standard tensile specimens from the AISI 316 stainless steel sheet have been prepared with the elliptical stress concentrators with their orientation 0°, 45° and 90° to the axis of loading. Continued changes in dimensions such as major and minor axis. The width w_1 &w_2 and the thickness 't'in the vicinity of deformation has been accurately measured at the applied loads. Based on the dimensional measurements the following calculations were made,

Major Strain = C_1= Ln ($D_{Inst.\ Major}/D_{0Major}$) -------- (4)

Minor Strain = $\square_2$ = Ln ($D_{Inst.Minor}/D_{0\ Minor}$) ---------- (5)

(Major Strain / Minor Strain)= ($\square_1/\square_2$) ----------(6)

True width strain, $_=$ C_{wt1}~ In ($W_{1i/}W_{1f}$) ;$C_{wt2\ =}$ In (W_{2i}/W2f) ---------- (7)

True thickness strain =C_1 = Ln (t_0/t_f) -------(8)

Plastic Strain Ratio = R $_1$= ($\square_2$ / $\square_1$) --------(9) $R_{2\ =}$ (C_{wt2}/ C_{wt1}) ----------- (10)

The above calculations have been carried out for all the orientations of elliptical stress concentrators and based upon these calculations, few important plots have been drawn in order to establish the material behaviour during tensile testing of thin AISI 316 stainless steel sheets.

III. Results And Discussion

3.1 Tensile Testing of Sheet specimens of AISI 316 Stainless Steel With and without Stres Concentrators

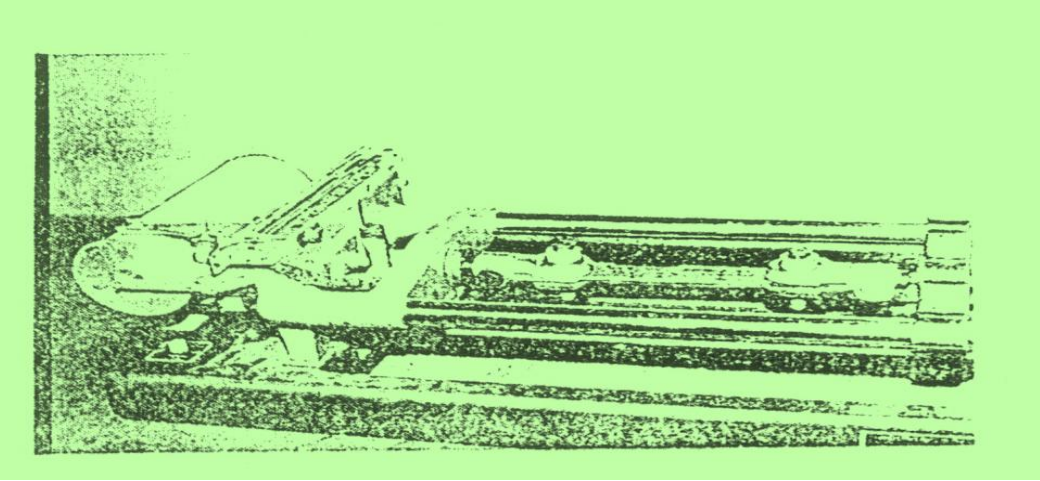

Figure l (a) Tensile Testing of AISI 316 Stainless Steel Strip,

Fig.1 (a) Shows the Actual Tensile Testing of Stainless Steel Sheet Specimen of AISI 316.stainless steel sheet on a Hounsefieldtensometer. However, fig.1 (b) shows the tension tested specimens under four categories, namely, when there has been no stress concentrator and when the stress concentrators were oriented with the major axis at 0^0, 45^0 and 90° respectively to the direction of loading. It can be clearly observed that when the inclination of major axis was 0^0 to the tensile axis, the ellipse enlarged in the direction of the loading, whereas, the minor axis Continued to decrease but the two ligament virtually fractured perpendicular to the axis of loading but with a little shift. Similar situation has been observed when the major axis ofthe stress raiser was inclined at 45^0 to the axis of loading, stress raiser acquired a shape where the major axis orientation continued to incline to the axis of tensile loading more and more when the applied load was enhanced. Dimensional changes in the minor axis have been onthe increasing trend and the fracture once again occurred perpendicular to the tensile loading. However, there is a substantial shift in fracture of both ligaments \:0\\ when the major axis of the stress raiser was perpendicular to the axis of loading, thinning on one of the ligament has been more and the fracture initiated from the inner tip of the major axis end points and propagated almost in alignment in both ligaments.

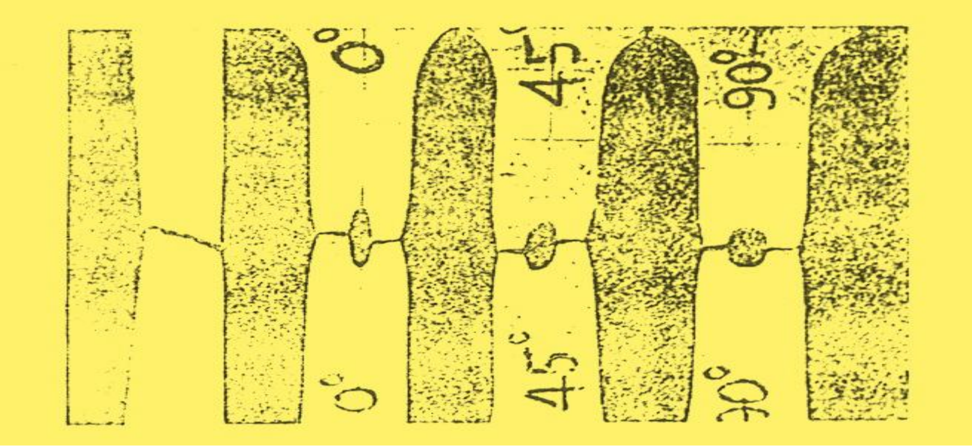

Figure l (b) Tensile Specimens of AISI 316 Stainless Steel after Testing

3S.1 Relation between Major Strain (e_1) and the Minor Strain (e_z) During Tensile Testing with and Without Elliptical Stress Concentrators Inclined Differently with the Axis of Loading

Fig. 2 shows the relationship between the major strain **(e_1)** and the minor strain **(e_2)** for AISI 316 Stainless Steel sheet specimen. The two curves corresponding to 0° and 45° orientation of elliptical stress raiser, the characteristic nature of these curves have been found to be quite similar to each other. However, it isfurther observed from these two curves that there has been a continuous increase in the major strain values when the minor strain also continued to increase. But the curve corresponding to elliptical stress aiser whose major axis was inclined to 90° to the axis of loading showed least enhancement in the major strain values whereas the minor strain increased quite rapidly. Fig. 2 further exhibit the four distinct regions where the variation of major strain (**e_1**) w.r.t. the minor strain (e_2)is either increasing or decreasing. Beyond the regions I andII the minor strain exhibits the tendency to decrease and prior to that, a tendency to increase when the major strain has continued to increase. Regions III and IV correspond to the decreasing trends of minor strains whereas the regions I andII describe the increasing trends of the major strains. However, in region IV for a stress concentrator with 90° orientation with the axis of loading, the major strain is found to decrease, but, at the same time there has been an increase in the values of the minor strain.

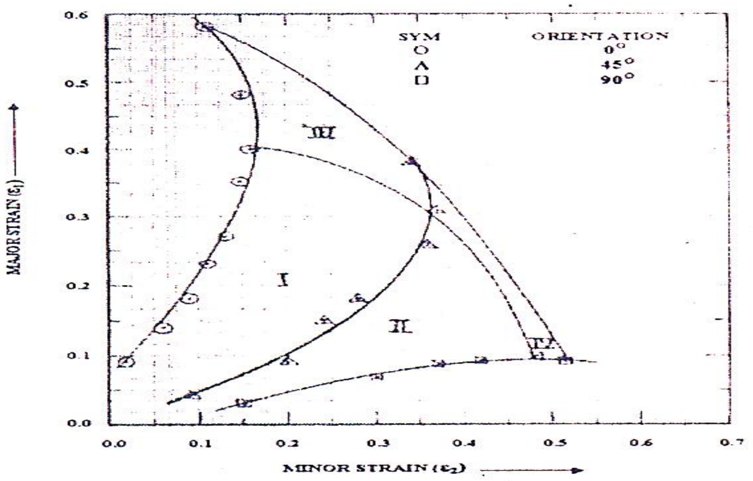

Figure 2 Relation between Major Strain (e_1) and the Minor Strain (e_2)

3.2 Relation between Plastic Strain Ratio and Major to Minor Strain Ratio

Fig.3 has been drawn between the plastic strain ratio{R = (e_w)/(e_t)} and the major to minor strain ratio {(e_1)/(e_2)}. The careful examination of the curves shown in fig. 3 reveal the very fact that with a very little or no variation in the ratio of {(e_1)/(e_2)}. the curve is almost perpendicular to (EI/E2) axis and parallel to the plastic strain ratio axis (R) indicating that its slope is infinity for the specimen containing an elliptical stress concentrator whose major axis is 90° to the axis of loading. However, the curve corresponding to 0° orientation of the major axis of the elliptical stress concentrator to the tensile axis is parabolic in nature whose vertex is at point. (EI/£2.R= 2.1,0.45). However, the change in the orientation of the major axis of the elliptical stress concentrator is 45° to the tensile axis of loading, the plastic strain ratio, R_p shot up by a mild change in the major to minor strain ratios and the curve becomes almost parallel to the plastic strain ratio axis.

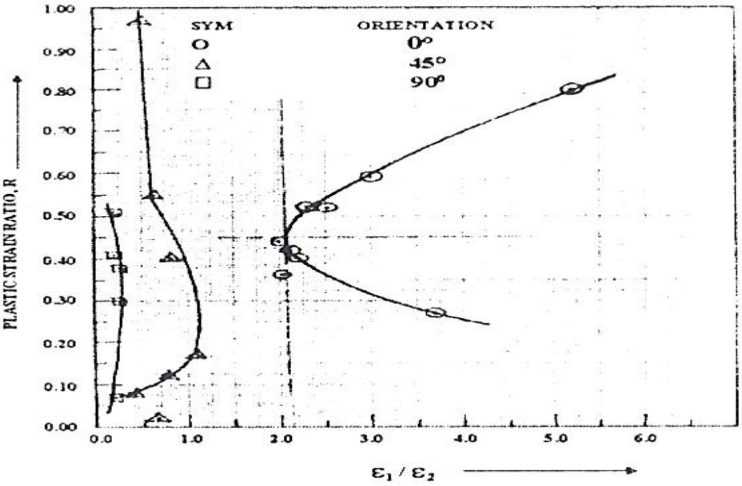

Figure 3 Relation between Plastic Strain Ratio (R_p) and Major Strain to Minor Strain Ratio(e_1/e_2)

IV. Conclusions

Based on the analysis of the experimental data and the calculated parameters, the following major conclusions were drawn:

1. It has been established that the crack initiation took place either at the inner tips of the minor or the major axis of the elliptical stress raiser perpendicular to the direction of loading and in particular perpendicular to the axis of applied load irrespective of the rolling direction and the orientation of the stress raiser.
2 The changes in the rotation of the major and the minor axis of the elliptical stress raisers were found to alter and this alterationwas of very complex nature and this is attributed to the material composition and the prior history or rotation of the stress raiser, and,
3. Irrespective of the rotation of the major axis dire o ction**(0°, 45°and 90^{n})** to the tensile axis, it is always found that just before the fracture, the major axis tended to lie closely parallel to the axis of loading. Summing up the findings of the present investigation, it is established that thin plates or sheets containing single/multiple or combined types of stress raisers will create a very complex situation and, therefore, the present investigation is simply an attempt to provide an insight view to awaken the scientists aware of the seriousness and possible design modifications in order to avoid the catastrophic failure/s in service.

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