Fracture Toughness Measurement of Aluminium and Steel Inserted Aluminium Using Numerical Method

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Abstract: The aim of the current work is to test the possibility of improvement of fracture properties of a shaft fabricated by press fitting a rod inside a tube and explore the effect of interface on the crack propagation. Measurement of Mode II fracture toughness is considered for this purpose. In this study numerical method developed by Yong Li and Viola based on Kienzler and Herrmann’s method by conducting a simple shear test on round bar specimen is adopted. Round bar specimens with a circumferential notch are subjected to shear test. Three specimens are prepared using Al6061T6 alloy tube inserted with rod of three different materials A6061T6 alloy, commercial pure Copper, and AISI1045 steel. Also a plain rod of Al6061T6 alloy is tested under shear to compare the results. Shear tests are conducted on Universal Testing Machine and fracture toughness values are calculated using modified Kienzler and Herrmann’s equations. The results indicated an improvement of 18% in the fracture toughness values in the case of A6061T6 alloy rod inserted A6061T6 alloy tube compared to the fracture toughness of plain A6061T6 alloy rod. And when steel rod is inserted inside the A6061T6 alloy tube an improvement of 33.33% in the fracture toughness.

Keywords: Fracture toughness; Mode II; layered shaft; shear test; Al6061 alloy

1. Introduction
Fracture is the major failure mode in mechanical structures which lead to breaking down of components without any prior indication before the estimated safe working life. Many researchers have conducted extensive work on fracture mechanics to understand the phenomenon and developed many theories. But still many areas are left unexplored. Determination of fracture toughness is a significant approach to estimate the fracture strength of the materials. Researchers have established many ways to measure the fracture toughness of the materials. But these methods suffer a major problem that, they require very expensive equipment and accurate preparation of the specimens and require lot of time and cost. To overcome these problems many researchers have developed nonstandard methods to measure fracture toughness which are economical in terms of time and money, but achieved good approximation of the results. In most of the cases this approximate values are well sufficient [1, 2].

2. Earlier Work
2.1 Stress Intensity Factor – KI
The analytical procedure used for Linear elastic fracture mechanics relates the distribution of stress field and its magnitude near the crack tip, the stress applied to a specimen, orientation, size, and shape of a crack. In fracture mechanics, the stress intensity factor K means the stress field ahead of the crack tip in a structural member. The unit of parameter K is MPa√m, which indicates that it depends on the nominal stress (σ) in the member and the size of the crack. Hence different members with cracks or defects can be loaded to different values of K. Fracture of the materials have been classified into three major modes, called opening mode or Mode I, shearing mode or Mode II, and tearing mode or Mode III. The Fig. 1 illustrates the three modes of fracture [3].
2.2 The Critical Stress Intensity Factor

A structural member with crack can be loaded up to the complete fracture when the stress intensity factor reaches a limiting value. This limiting value before fracture is called fracture toughness, $K_C$, which is a material property. The crack propagates when $K_I \geq K_{IC}$ is the fracture criterion by $K_{IC}$. ASTM E-399 is the standard test methodology for determination of plane-strain fracture toughness ($K_{IC}$) of metallic materials which fail predominantly in a brittle manner. The standard is designed to ensure that linear-elastic conditions prevail throughout the test. This is achieved by requiring a sufficiently large specimen for the particular toughness. Due to the possibility of brittle fracture in the presence of the notch, for the validation of fracture toughness values the plane-strain condition is required. The measured critical stress intensity factor (SIF) is then called the plane-strain fracture toughness for mode I (designated as $K_{IC}$) and is a true material property. It is important to note that the $K_{IC}$ value to be obtained must be known or estimated before a $K_{IC}$ test specimen is machined [5]. This test method (ASTM E-399) is not practical for materials showing significant plasticity before the beginning of stable crack growth because of the size limitations. Industry requires a simple straightaway approach to investigate the failed members.

Plane-strain fracture toughness testing of aluminum alloys is performed essentially in accordance with ASTM E 399 method [6]. However there are certain areas in which experience has shown a need for tighter requirements for aluminum alloys than specified in test method E 399, and others where some relaxation of validity requirements is justified on the basis of controlled experimental studies. The application of this practice will be of particular importance for quality assurance and material release in cases where valid plane-strain fracture toughness data cannot be obtained because of limitations of specimen size or some aspect of the fatigue cracking or resultant fatigue crack front, or both. To obtain valid $K_{IC}$ value requires large size specimens as specified in ASTM E399. But in many cases it is practically difficult to obtain the required specimen size of the material to be tested. This necessitates the investigation of small sized specimen in fracture toughness test. Circumferentially notched round bar specimen (CNRB) is promising specimen geometry in this context [7].

The traditional standard fracture mechanics test procedures are very expensive, consuming longer time and require bulky specimens. Also, sometimes required size of sample may not be produced. The above said limitations lead to a development of a new approach for the determination of stress intensity factor (KI) using circumferential notched tensile (CNT) test specimens. This (CNT) is the smallest possible specimen which can give a valid plane-strain crack loading conditions within ± 3% of the values obtained using ASTM standard compact tension (CT) test specimens [8].

It is sometimes impractical and difficult to meet the dimensional requirements of specimens according to standard test procedures; may be due to insufficient volume of material available or due to geometric unsuitability of the of the sample material such as in pressure vessels and piping (PVP) systems materials. Adequate toughness is an essential characteristic of PVP system design. From the available material if it is not possible to prepare a specimen that can meet the specimen size criteria as per ASTM E399 specifications, then it is impossible to obtain a valid $K_{IC}$ according to E 399. To overcome the inherent limitations of standard plane-strain fracture toughness test procedures, various new test approaches are proposed by investigators using either spiral notch torsion test or circumferentially cracked round bar subjected to torsion and tensile load or single edge rod specimen under mode I loading [9]. Standard procedures for fracture tests require elaborate specimen preparation, pre-fatigue cracking of the notch, and fatigue crack growth rate measurement, thorough analysis and interpretation.
of the data; which are all very expensive and time consuming. Furthermore, to obtain effective material data for all cases of specific batch of material, considerable numbers of tests required to be conducted. Therefore any method that can decrease the number of experimental tests and improve and optimize this process, and reduce the overall cost without compromising safety issues, is an advantage [10].

Neelakantha et al. conducted experiments on circumferentially notched round rod specimens of high strength aluminium alloy Al2014T651 and calculated $K_{IC}$ and fatigue crack growth rate. The test procedure followed was same as explained earlier [11]. The round rod specimens with ‘V’ notch were pre-cracked on fatigue testing machine and then loaded till failure on universal testing machine. The Mode I fracture toughness was calculated using available equations. The values thus obtained were very close to the standard $K_{IC}$ recorded by many researchers using standard compact tension (CT) and single edge notched bend (SENB) specimen configurations. The study reveals that use of circumferentially cracked round bar specimens to determine fracture toughness and fatigue crack growth rate is a modest, reliable, quicker and cost-effective method. This methodology was later used by many researchers and was recommended for fracture toughness as well as crack growth measurement as a standard test method [12].

2.3 Advantages of Using CNRB for Fracture Toughness Test

Common practice is to use a circumferential 60°V-notch in round specimens with cross-sectional area under the notch equal to half that of the un-notched section. The surface effects and residual stresses at the notch root are very influential in this geometry because of small volume of the material at the notch root. The root radius is generally 0.13 mm or less. The diameter of notched section and the diameter at the root of the notch should be given a close tolerance within ± 25 microns [13].

The analytical fracture behavior of a CCRB specimen in tension is studied and the maximum fracture toughness as a function of specimen size is evaluated [14]. It is a practical test specimen used by various researchers for determining the fracture toughness [15]. Christopher et al. [16] lists following advantages:

- The CCRB specimen under tension is an axisymmetric geometry which develops uniform stress triaxility along the circumferential notch front.
- The geometry allows equal access to the notch tip, making it ideal for stress corrosion cracking tests.
- Geometry is ideal for fracture toughness testing in mixed mode I and III.
- The geometry is attractive for dynamic or impact fracture toughness testing.

In the linear elastic fracture mechanics study of cracked surfaces determination of the stress intensity factor (SIF) plays a vital role. Three dimensional analysis would be required for the study of crack problems in round bar specimens having surface or part-through cracks. However, three dimensional analysis are complex in nature and exact solutions for surface cracks in round bars are not available. It has been proved by many researchers that methods involving minimum amount of computational work are suitable for the determination of strength of cracked bodies, even if the accuracy is lower [18]. E. Viola et. al., used two simple methods to determine quick and approximate values of stress intensity factor in cracked beams shown in Fig.2. The methods are, a) Kienzler and Herrmann’s Method; b) Section Method. The schematic of the specimen used in their study is as shown in the Fig.2.

![Figure 2. Cracked round bar and cross-section at the crack](image)

In the current study the fracture toughness of aluminium rod and steel rod inserted aluminium beam is determined by Kienzler and Herrmann’s Method.

2.4 Kienzler and Herrmann’s Method
It’s a numerical method of fracture toughness evaluation which gives approximate values which are sufficient for safe design of structures. This method enables to evaluate $K_I$, $K_{II}$, and $K_{III}$ fracture toughness from simple tests of bending, shear and torsion respectively. The results obtained by this method for the beams with symmetrical cracks about the neutral axis are matching well with other known numerical results, and can thus serve as a good estimation tool in engineering design. [17].

When a beam of circular cross section with an edge crack is subjected to the bending moment $M$, the mode I SIF $K_I$ is given by Equation (1).

$$K_{II} = \frac{M}{R^{1/2}} F_M(\eta)$$

(1)

Where, $F_M(\eta)$ is the geometric function under bending moment [17].

If a cracked beam of circular section is subjected to a torque $T$, the expression of the SIF is given by Equation (2),

$$K_{II} = \frac{T}{R^{1/2}} F_T(\eta)$$

(2)

Where, $F_T(\eta)$ is the geometric function under torsion [17].

Similarly in the case of a cracked beam with circular section is acted upon by a shear force $S$, the expression for $K_{II}$ is given by Equation (3),

$$K_{II} = \frac{S}{R^{1/2}} F_S(\eta)$$

(3)

Where, $F_S(\eta)$ is the geometric function under shear [17].

### 3. The Current Work

In the present work, fracture toughness of Aluminium 6061T6 is determined using Kienzler and Herrmann’s Method and is compared with the fracture toughness of AISI 1045 medium carbon steel rod inserted inside aluminium tube. The aim is to enhance the fracture toughness of aluminium by reinforcing steel rod. The Mode I stress intensity factor $K_I$ is measured by conducting bending test on UTM. Also the Mode II fracture toughness $K_{II}$ is determined by conducting double shear test on UTM. Two types of specimens are prepared, one plain aluminium rod and second type is steel rod inserted inside aluminium tube by interference fitting. Both the specimens are of outside diameter 12 mm. The steel rod is 6 mm diameter solid. A circumferential crack is machined at the center of bending specimens. On the shear test specimen a very shallow crack is made using a hacksaw blade. The minimum crack depth required as available in the literature is assumed for shear test. Five specimens are tested in both the bending and shear.

After conduction of tests the fracture toughness is determined using Kienzler and Herrmann’s Method which allows the quicker calculation of fracture toughness. Though it gives approximate value, in terms of time consumed it is beneficial, as the value obtained is sufficient for most of the applications.

### 4. Results and Discussions

The calculated values of fracture toughness ($K_I$) due to bending moment are illustrated in the following Table 1. The Table 2 lists the $K_{II}$ fracture toughness values determined by shear test.

| Specimen No. | $K_I$ Fracture toughness of solid aluminium rod (MPa√$m$) | $K_I$ Fracture toughness of steel rod inserted aluminium (MPa√$m$) |
|--------------|----------------------------------------------------------|---------------------------------------------------------------|
| 1            | 35.8                                                     | 41.3                                                          |
| 2            | 35.6                                                     | 41.5                                                          |
| 3            | 35.8                                                     | 41.0                                                          |
| 4            | 36.1                                                     | 41.2                                                          |
| 5            | 35.7                                                     | 41.2                                                          |

| Specimen No. | $K_{II}$ Fracture toughness for Two Types of Specimens |
|--------------|---------------------------------------------------------|
| 1            | 41.3                                                    |
| 2            | 41.5                                                    |
| 3            | 41.0                                                    |
| 4            | 41.2                                                    |
| 5            | 41.2                                                    |
There is an improvement of 14.5% in K\textsubscript{II} fracture toughness compared to solid aluminium rod. There is an improvement of 14% in the fracture strength, whereas the weight of steel rod inserted specimen increases by 44.5% but at the same time there is a saving in the costlier material like aluminium. Usually the strength and fracture toughness contradictary parameters, by combining high strength steel and tougher material like aluminium both toughness and strength are combined. This is also evident from the K\textsubscript{II} fracture toughness values obtained by shear test. There is an improvement of 14.5% in K\textsubscript{II} values in the case of steel inserted aluminium.

### Table 1: Fracture Toughness Values

| Specimen No. | K\textsubscript{II} Fracture toughness of solid aluminium rod (MPa√m) | K\textsubscript{II} Fracture toughness of steel rod inserted aluminium (MPa√m) |
|--------------|-------------------------------------------------|-------------------------------------------------|
| 1            | 21.3                                            | 24.0                                            |
| 2            | 21.4                                            | 23.8                                            |
| 3            | 21.1                                            | 23.9                                            |
| 4            | 21.2                                            | 24.2                                            |
| 5            | 21.1                                            | 24.4                                            |

The K\textsubscript{II} fracture toughness calculated for bending tests indicate that the rod inserted tube is having higher fracture toughness compared to solid aluminium rod. There is an improvement of 14% in the fracture strength, whereas the weight of steel rod inserted specimen increases by 44.5% but at the same time there is a saving in the costlier material like aluminium. Usually the strength and fracture toughness contradictory parameters, by combining high strength steel and tougher material like aluminium both toughness and strength are combined. This is also evident from the K\textsubscript{II} fracture toughness values obtained by shear test. There is an improvement of 14.5% in K\textsubscript{II} values in the case of steel inserted aluminium.

5. **Conclusion**

Enhancement of fracture toughness is a major challenge to the design engineer and always the strength and toughness does not exist together. The current work is an attempt to improve the fracture properties of aluminium. Bending and shear tests are carried out to determine the failure load and using Kienzler and Herrmann’s Method the fracture toughness is measured. An improvement of around 14% is obtained for both K\textsubscript{I} and K\textsubscript{II} fracture toughness.

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