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Short communication(T-1)

STRUCTURAL FAILURE ANALYSIS OF ROCKET MOTOR

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ABSTRACT

Out of various mode of failure of rocket motor, material failure is the main cause of concern. This may be due to either the micro cracks present in the material or caused during manufacturing process. Ultimate tensile strength and thickness of the material are the parameters responsible for structural failure. The fracture strength of a classical brittle material is inversely proportional to the square root of the crack length. Stress intensity factor of the material when reaches its critical value called critical stress intensity factor, it fails as brittle fracture. It is a material property and the controlling factor to select suitable material for rocket motor. It decreases with the increase of material thickness. A thin plate sample of steel SAE 4130 having a central crack has been considered. The sample is stressed under tensile load in plane stress condition in universal testing machine. On reaching a particular stress, the crack begins to propagate and the same is analysed using Feddersen approach. Crack generated due to circumferential stress developed in the rocket motor tube as result of maximum propellant gas pressure should be less than half the thickness of the material. Under this condition it can be predicted that no structural failure would occur. The paper also suggests the criteria for safe design to withstand the severe conditions through which a rocket motor undergoes. The sample being the actual material certain data has been suitably modified however, keeping the working principle intact.

Key Words : Failure, Rocket Motor, Analysis, Tensile Strength, Stress intensity factor, Linear elastic fracture mechanics, Crack

INTRODUCTION

Launching of rocket and achieving its mission involves colossal amount of resources in terms of man, machine and material. These are put through logical and inventive use of science, engineering and technology. Successful amalgamation of all these resources results in successful mission. All the resources discussed here ultimately measured in terms of money and the amount is enormous. Failure of a rocket to achieve its mission will thus have a direct effect on both economy and scientific progress of a nation. Considering the failure of rocket motor, it may be attributed to various reasons. These are either caused by error during operation or due to defect during manufacturing. Human error is individualistic and thus needs to be resolved at individual level. The manufacturing defects however may be resolved by failure analysis and incorporating the points recommended by the analysts. Out of various mode of failure, material failure is the main cause of concern. Failure of rocket motor can be broadly classified as failure of rocket motor components or failure of propellant. Component failure like case burst, nozzle failure, bore choking; GN & C failure, structural failure, PLI bond-line failure and ignition failure are generally observed[1]. There may also be a failure due to loss of control by hot gasses ejected out through case breach[2]. Some of the major propellant failures are case breach, debonding, propellant structural failure, combustion instabilities and variation in equilibrium combustion pressure beyond acceptable limit. Prediction of failure can be done by employing various methods/principles like Scaling Equations of

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Ballistics Modeling[3] and Linear Elastic Fracture Mechanics.

AIMS AND OBJECTIVES

The structural failure and case breach of solid propellant rocket motor is primarily due to weak/faulty casing (tube) materials. In this paper prediction of case breach and structural failure is brought out using Linear Elastic Fracture Mechanics (LEFM). The paper also suggests the criteria for safe design to withstand the severe conditions through which a rocket motor undergoes.

MATERIAL AND METHODS

Ultimate tensile strength and thickness of rocket motor material are the parameters responsible for structural failure. Analysis of failed structural component reveals that the failure is brittle in nature due to initiation and propagation of cracks. The influence of crack is analysed to predict the failure using the science of fracture mechanics. The fracture strength of a classical brittle material is inversely proportional to the square root of the crack length[4]. The elastic stress in the vicinity of crack tip is expressed by a stress field parameter K_1 called the stress intensity factor. Values of K_1 can be determined numerically and verified experimentally. For a centre crack length $2b_0$ in an infinite thin plate subjected to a uniform tensile stress σ the stress intensity factor K_1 is given by

$$K_1 = \sigma\sqrt{\pi b_0} \quad \dots \quad \dots \quad (1)$$

If the crack continues to grow in a semicircular configuration with radius b_0, it would cross the tube thickness t when b_0 equals to t and case breach failure will occur. Under this condition the value of stress intensity factor K can be calculated as

$$K = \sigma\sqrt{\pi t} \quad \dots \quad \dots \quad (2)$$

It may be deduced that no failure take place if K is below the critical value of K^1. A critical value of K^1 is used to define the conditions that produce brittle fracture as the case in point. This is called critical stress intensity factor K_c which is the plane-strain fracture toughness of the material. It is used to predict the brittle structural failure of rocket motor. By knowing its value the maximum allowable stress to prevent brittle fracture for a given flaw size can be computed. By analyzing the crack size of a specimen (called Centre Cracked Tension (CCT) specimen) under tensile load and comparing the same with a compact Specimen (CS) under similar condition, Kc can be determined. This method is known as Feddersen approach[5] which has the basis that stress is a function of crack length propagation under tensile load. Considering a thin plate having a central crack of length b_0 which is under tensile load in plane stress condition. The stress in the specimen will go up as the load is increased. On reaching a particular stress, the crack will begin to propagate at slow but stable state. If the load is kept constant at this stage, the crack will continue to propagate till a specific crack length is reached. This crack length is called the critical crack length and the corresponding tensile stress is known as critical stress intensity factor K_c. Beyond this stress the crack becomes unstable and propagates faster leading to fracture. If $2b_c$ is the critical crack length for which the failure occurs and α is a parameter that depends on the specimen and the crack geometry, then

$$K_c = \alpha\sigma\sqrt{\pi b_c} \quad \dots \quad \dots \quad (3)$$

By Feddersen approach, for a plate width W, we get α as

$$\alpha = \sqrt{\sec\frac{\pi b_c}{W}} \quad \dots \quad \dots \quad (4)$$

K_c varies with thickness of the material. For smaller thickness the material behaves under the category of plane stress condition and then to plane strain condition as the thickness is increased. It can be seen that critical stress intensity factor increases with the decrease of material thickness. However, by increasing the material thickness to reduce stress intensity factor, dead weight of the motor would be more leading to reduction of pay load for other factors remaining constant. Hence, there is a requirement to optimize the stress intensity factor with material thickness. As shown in **Fig 1,** the value of K_c becomes asymptotic to a minimum value with increasing thickness; this value is known as plane strain critical stress intensity factor[6] and denoted as K_{1c}. It may be considered as material property. The change of K_c is shown for the given specimen thickness of high tensile strength steel SAE 4130, widely used in defence production including manufacturing of seamless tubes of artillery rocket[7].

The concept of fracture mechanics is applicable under the condition where no yield occurs i.e. for linear elastic or brittle failure. It may be seen in Eq (2) that as b_c approaches zero σ at the crack tip approaches infinity resulting in occurrence of tip plasticity. However, this plastic zone is very small as compare to crack length and has negligible effect on K_c. There is thickness restriction to achieve plane strain condition and valid measurement of K_c. Hence, Linear Elastic Fracture Mechanics is applicable to high strength materials e.g. SAE 4130.

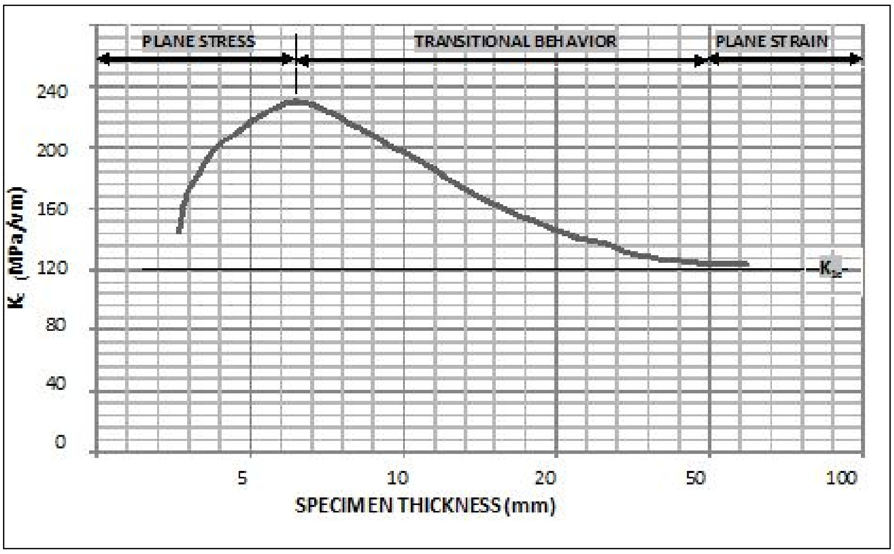

Fig. 1 : Relation between critical stress intensity factor and material thickness

RESULTS AND DISCUSSION

To carry out LEMF analysis of Steel SAE 4130 the following data have been considered :-

(a) Yield strength : σ = 950 MPa
(0.2% Proof stress)
(b) Tensile Strength : σ_t = 1200 MPa
(c) Inside diameter of : D = 200 mm
rocket motor tube
(d) Thickness of : t = 2 mm
tube material
(e) Width of the : w = 40 mm
specimen tube
(f) Initial crack length : 2a = 12mm
in the specimen
(g) Max propellant : P = 12 MPa
gas pressure

Table 1 : Experimental Data

S/N	Load (KN)	Increase in crack length (mm)	Stress (MPa)
1.	62.47	0.42	1061
2.	60.49	0.56	1035
3.	58.63	0.60	1027
4.	58.80	0.72	1004
5.	57.03	0.90	970
6.	55.10	1.09	934

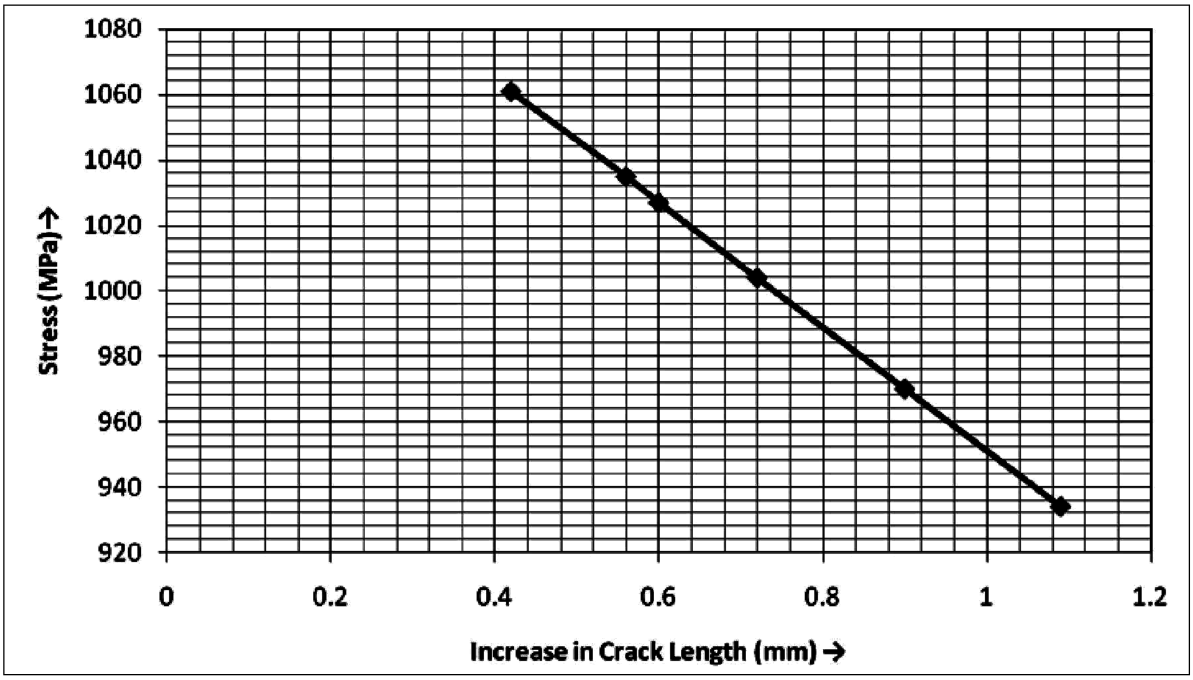

Fig. 2 : Plot of Stress Vs Increase of crack length

Experimental Data and Plot of LEFM Analysis

Experiment of the specimen has been carried out in universal testing machine. The tabulated data is given in **Table** 1 and the plot is given in **Fig 2**.

Sample Calculation

(a) Circumferential stress $= \sigma_c = PD/2t = 600$ MPa

(b) Stress intensity factor K $= \sigma\sqrt{\pi t} = 75.7\ \text{MPa}\sqrt{m} = K_c$

(c) By Feddersen approach, for $b_0 = t$, we get, $\alpha = \sqrt{\sec\frac{\pi t}{W}} = 1$

(d) Critical crack length along the length (X direction) and width (Y direction) of the specimen for which the failure occurs due to circumferential stress can be calculated from the relation, $K_c = \alpha\sigma\sqrt{\pi b_c}$ and using $\sigma = \sigma_c$, we get $b_c = 5.06$ mm (less than initial half crack length, a = 6 mm)

(e) For safety, $\sigma_c < ⅔\,\sigma$, here $⅔\,\sigma = 633.3$ MPa (here σ_c is within limit).

CONCLUSION

It needs to be noted that the selected material be able to withstand the circumferential stress in such a manner that the crack length in X and Y direction should be less than critical crack length. Also the maximum circumferential stress due to propellant gas pressure should be less than two third of yield strength of the material. Critical Stress intensity factor K_c is the controlling factor to determine the suitable material for rocket motor. It is also useful to select a material thickness which should not fail in plane strain condition and ensure fracture only under plane stress condition.

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