DETERMINATION OF THE CRITICAL CRACK LENGTH a_{IC} IN TURBINE DISCS

Nie Jingxu (聂景旭), Hong Qilin (洪其麟), Nie Cong (聂 聪)
Beijing Institute of Aeronautics and Astronautics, China

ABSTRACT

A turbine disc is known as one of the most important parts of a jet engine. In the design and analysis of the damage tolerance for turbine discs, it is necessary to determine exactly the critical crack length a_{IC}. Using the cracks at the bottom of fir-tree slots of the first stage turbine disc in an existing engine as an example, by means of the breakdown test and elaborate theoretical calculation, this paper presents the criterion and the solution algorithm to determine the critical crack length a_{IC}, and suggests that the condition under which the engine could not normally operate be regarded as the critical state for the crack. In view of the complexity of turbine disc shape and loading conditions, the authors have employed the J integral in the elasto-plastic fracture mechanics and the "twice evaluation algorithm" for evaluation J-integral which has been proved to be a simpler and more accurate method than those presented in the literature.

I. INTRODUCTION

Since the shape and the load conditions of turbine discs are complicated, it is necessary to investigate what criterion and solution algorithm can be applied to determine the critical crack length. On the basis of fracture analysis, the breakdown tests were carried out. Employing the test results and the theoretical analysis, we have obtained the criterion and solution algorithm to determine the critical crack length a_{IC} of turbine discs. The criterion and solution algorithm obtained in such a way can generally be used for analyzing the damage tolerance of the rotating

components in jet engines.

II. BREAKDOWN TEST OF THE TURBINE DISC WITH CRACKS

The breakdown tests are carried out under the room-temperature condition. Accordingly, there is no thermal stress in the discs. Since the thermal stress is compressive (negative) at the rim and tensile (positive) at the center of the turbine discs, under real operating conditions, so the stress under test condition at the center is smaller and at the rim, it is larger than that under operation conditions. This is conservative for the breakdown test which is aimed at checking the load-bearing capacity of the rim of the turbine discs. The prefabricated cracks of the testing discs are selected in such a way that only a pair of cracks are distributed symmetrically along the perimeter of each disc. This is supposed to be the most dangerous condition. To determine the length a_0 of the prefabricated cracks, it is required that the failure rotating speed of the testing discs be in the range of 10000-15000(r.p.m.). The data of the testing discs are listed in table 1[1]. Figure 1 presents a picture taken at the instant when the disc is broken down along the prefabricated crack.

Fig. 1. The photograph of the disc taken at the break instant

Table 1. Data of break test

Specimen	Disk number	Slot number with arti-ficial crack	Length of arti-ficial crack	Blade lost			Rim broken		
				Δa mm	a^{*}_{IC} mm	n_{th} rpm	Δa mm	a^{**}_{IC} mm	n_f rpm
1	A11269-6-:	70 32	30.05 29.48	1 2	31.05 31.48	12280 12280	14.558 6.24	44.608 (not broken)	13520
2	1E370-4-336	42 4	23.7 22.48	4.36 6.47	28.06 28.95	13550 13550			
3	5429110-1V	27 65	32.75 33.74				12.4 12.184	44.65 45.928	12810 12810

III. DETERMINATION OF THE CRITICAL CRACK LENGTH a_{IC}

According to the results and phenomena of the breakdown tests, the evaluation of the critical crack length of the turbine disc is obviously a problem of the elasto-plastic fracture mechanics. We choose the J-integral to characterize the crack tip parameters. Because of the complicated geometric shapes of the turbine disc and the bottom of fir-tree slots, we have to employ a numerical method-the finite element method to calculate the J-integral. The method has been proved in practice to be quite convenient and simple in computation. The loads at the bottom of the fir-tree slots, however, are also rather complicated. There exist the external transmitted force, body force, thermal stress and residual stress, etc., thus, computation efforts for the non- linear finite element analysis are needed, and great difficulties for calculating the J-integral are encountered. Therefore, we suggest that the "twice evaluation algorithm" be used to solve the problem, i.e. at first, the J_{IE} is evaluated by means of the linear elastic fracture mechanics, in which the superposition principle car be applied to evaluate the J-integral under the complex load condition; secondly, a plastic correction with iterative procedure is made on the values from the linear elastic fracture mechanics[2], then J_{IP} is obtained.

The fifth pair of serrations are included in the analysis domain of the refined mesh. This not only takes into account the effect of geometric shape of the serration on the parameters at the crack tip, but also obtain: the displacement u_5 at the tip of the fifth pair of serrations.

1. Computation Analysis of the Test Discs

J_{IP} vs a and u_{5P} vs n curves are shown in Fig. 2 and Fig. 3 respectively.

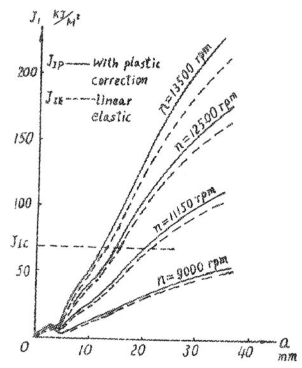

Fig. 2 The J_I- a curves of testing disks

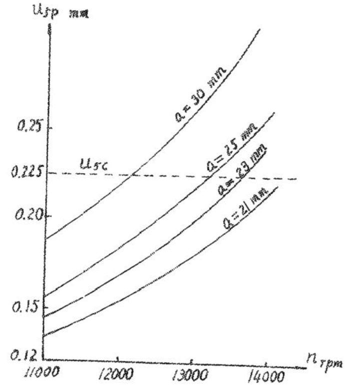

Fig. 3 The u_{5P}- n curves of testing disks

According to the data obtained in the breakdown test, we find J^{*}_{IC}= 247.8KJ/M. And when the blades are broken away from the disc, the serration tip displacements u_5 at this moment can also be obtained as u_{5C}=0.225 mm. In addition, J_I=J_{IC} can be regarded as the critical condition for the crack to start propagating in the discs.

Using the three critical conditions: J_{IC}, u_{5C} and J^{*}_{IC}, and the calculated curves mentioned above, the curves of critical values can be obtained in a-n coordinate system as shown in Fig. 4.

Isopleth curve u_{5C} intersects the isopleth curves J_{IC} and J^{*}_{IC} at points A and B, respectively. Therefore, three areas can be identified in Fig. 4. Area I is a low rotational speed zone, only when the disc crack is very long, can the critical condition be reached. The cracks do not start to propagate yet when the blades are broken away. Area II is a usual rotational speed zone, in which the machine is operating. When the crack length a is larger than a certain value, the critical condition may be reached. The order to cause failure is: the crack starting propagation--the blades breaking away--bursting. Area III is a zone of the speed higher than operating speed. Since the loads are large, the critical condition may be reached for a relatively small crack length. The order to cause failure is: starting propagation of the crack--bursting.

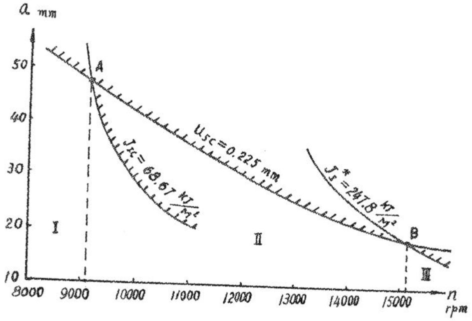

Fig. 4 The a-n curves taking u_{5C}, J_{IC}, J^*_{IC} as the critical conditions

When determining the critical crack length of the turbine disc, we define the operating condition (mainly the rotational speed) according to the characteristics of the engine and the user's requirements to the engine. The engine under investigation in this paper is operated at the speed in Area II. The order of reaching the critical condition is: starting propagation of the crack--blades breaking away--bursting. Therefore, it is not reasonable that the bursting of the disc is regarded as the critical condition. It might be suggested that the condition under which the turbine canno operate normally (blades breading away for example) is taken as the critical condition. But it should be noted that the cracks have started propagating before the blades are broken away, we suggest that starting propagation of the crack be the criterion to determine the critical length of the cracks in turbine discs, although this is a little bit conservative criterion.

2. Determination of Critical Crack Length a_{IC}

According to the criterion mentioned above, we can determine the critical crack length a_{IC} for a turbine disc under operation, which differs from that under testing condition mainly on the temperature field. It is necessary to consider the thermal stresses in practical discs. Since the thermal stresses at the bottom of the slots are negative (compressive), for the sake of safety, the operating condition under which the absolute values of thermal stresses are minimum should be selected. We therefore, choose the temperature field of cooling engine to calculate the thermal stresses[3]. The engine should be overspeeded up to 122%, according to the standard, i.e. the rotational speed of the engine is 13360 (r. p. m.). The J_{IP} vs a curves are given in Fig. 5. Isopleth curves J_{IC} and u_{5C} in a-n coordinate systems are shown in Fig. 6.

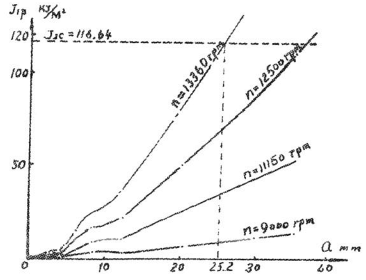

Fig. 5 The J_{IP}-a curves of the disk in a practical engine

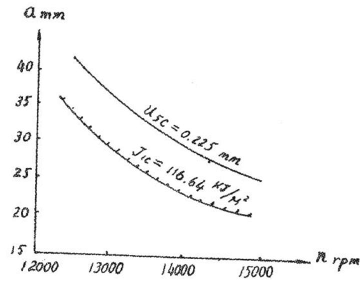

Fig. 6 The a-n curves of a practical disk taking u_{5C}, J_{IC}, as the critical condition

The J_{IC} value of the material under working temperature of the engine is J_{IC}=116.64KJ/M, from which the critical crack length can be determined as a_{IC}=25.2 mm. If we choose an appropriate safety factor the critical crack length in practical use can be determined.

IV. CONCLUSIONS

1. As the turbine discs are made of the material with high fracture toughness, it is reasonable to suggest that the condition under which the engine cannot operate normally be the critical state. It is beleived that this criterion can also be used in determining the critical states of other in discs and disc-shaped components operating at high speed.

2. Under the practical engine condition, the failure caused by the crack at the bottom of the fir-tree slots of the first stage turbine disc may probably follow the following stages: crack initiation--blades breaking away--disc rim bursting. It is appropriate that the crack initiation (J_{IC}) is used to determine the critical crack length a_{IC} of a turbine disc, and it tends to be safer.

3. In view of the difficulty of calculating the nonlinear J-integral under complicated loads, the "twice evalution algorithm" has been presented in this paper. The practical application of this algorithm has shown that it is convenient for application and the computation accuracy is high.

4. The deformations of rotor parts in modern jet engines are strictly limited. For larger deformation at these parts would destroy the normal operation of an engine. Therefore, it would be reasonable that the direct deformation due to existance of cracks at these important locations should be used as a criterion for determining the critical condition.

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