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Original Research Article

Numerical Calculation of Fracture Parameters in Grooved Rotating Disc Containing Three-dimensional Semi-elliptical Crack Under Mixed Mode Loading

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ABSTRACT

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In this study, a comprehensive investigation of the fracture parameters in a grooved rotating disc containing a three-dimensional semi-elliptical crack under different working conditions has been investigated. In this regard, three models of radial, circumferential, and inclined crack with an angle of 45 degrees have been considered in the rotating disk, and the fracture parameters under mixed mode loading (I, II, III) have been extracted. The effects of various parameters such as rotational speed, crack location, aspect ratio, material, and presence of grooves on SIFs and crack opening displacement have been studied simultaneously. The finite element results indicated that in the crack with a low aspect ratio (0.4 and 0.6) where the shape of the crack is more like a semi-elliptical, the maximum value of the mode I SIF occurs at the central point of the crack front, while the crack with a high aspect ratio (0.8 and 1) where the shape of the crack is more like a semicircular, the maximum value of the mode I SIF occurs at the free surface of the crack. The mode II SIF for the rotating disk containing an inclined crack before the central point of the crack front has the highest value for steel, titanium, and aluminum rotating disk, respectively. Also, the numerical results indicated that the highest value of the SIF is related to the grooved rotating disk containing a circumferential crack, and the lowest value of the SIF is for the grooved rotating disk containing a radial crack.

Introduction

Nowadays, studying and evaluating the useful life of rotating disks in industry is very important. One of the factors that greatly affects the life of rotating disks and can reduce their useful life is the initiation and propagation of cracks in these disks. Several factors expose the rotating discs to the initiation of cracks, the aggravation of which causes the crack to grow and cause irreparable damage. Therefore, it is very important to study rotating disks from a fracture mechanics point of view. When the rotating disk is subjected to fluctuating loads and stresses for a long period, microcracks are formed inside the disk, which grow and connect as the load increases, forming a semi-elliptical crack [1]. In the field of studying rotating disks from the point of view of fracture mechanics and numerical calculation of fracture parameters, various investigations have been carried out so far. In this regard, Fekur and Ghoreishi [2] calculated the mode I stress intensity factor in a rotating disk with radial and

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circumferential cracks. They also investigated the effect of composite patches on SIF values of SIFs in rotating disks. The effect of calculating SIFs on cracked rotating disks containing mixed mode by the boundary element method was proposed by Park [3]. The results show that as the crack deviation angle increases, the first mode's SIF decreases, and the second mode's SIF increases. The accurate determination of the SIFs in a rotating disk containing an inclined crack with a desired position was carried out using the finite element method by Wilson and Migued [4]. They studied the accuracy of extrapolation methods, virtual crack development, and J-integral to evaluate the combined modes of SIFs using the rotating disk problem containing a radial crack. They showed that the two methods of virtual crack development and J-integral provide the most accurate results. A numerical investigation of crack growth rate in three types of a cast iron rotating disk, compact core, and graphite was done by Shikida et al. [5]. They showed that the range of SIFs could not relate the crack propagation rates in the three disks to each other. Meanwhile, J integral can establish this relationship through finite element analysis. Finally, the range of the modified SIF was extracted by the material's tensile strength to correlate the crack propagation rate in all three disks. Aliabadi and Portella proposed the analysis of mixed-mode crack growth inside the rotating disk using the double boundary element method [6]. In this article, the incremental crack growth process based on the maximum principal stress criterion was simulated, and finally, the analysis of the incremental crack growth process was studied for several rotating disks containing edge cracks. Reference references include a review of other numerical methods for calculating failure parameters [7-11]. Extensive research has been conducted in the analytical calculation of failure parameters in rotating disks. In this regard, Qajar et al. [12] calculated the stress intensity factor in two thin and thick rotating disks containing surface cracks using two-dimensional weight functions. The purpose of this research was to develop a two-dimensional weight function for rotating disks containing semi-elliptical longitudinal cracks. The results showed that increasing the length-to-thickness ratio in rotating disks leads to an increase in the stress intensity factor for cracks with a high length-to-depth ratio. Tan has proposed the use of boundary integral equations for 3D linear elastic fracture mechanics analysis in rotating disks with corner cracks [13]. The study of the weight function of a boundary element for a rotating annular disc containing an internal edge crack with rotational speed and different lengths was carried out by Lorenzo and Cartwright [14]. The boundary element method, together with a general representation of the weight function, led to the emergence of integrals from which stress intensity coefficients and crack surface displacements can be obtained. Rook and Tweed [15] calculated the stress intensity coefficients in rotating disks with edge and internal radial cracks using two coupled single integral equations. A review of other numerical methods for calculating failure parameters is included in references [16-18]. Less research has been done in the field of experimental calculation of fracture parameters in rotating disks than in numerical and analytical methods. Among the research carried out in this field, the work of Bilawal et al. [19] can be mentioned for the calculation of SIFs in rotating disks with radial cracks using the photoelasticity method. Using the method of superposition and matching between the computational and laboratory results, as well as between the dynamic and static critical values, they proved that failure occurs when the value of the stress intensity coefficient is greater than or equal to the value of the fracture toughness of the material. The study of crack tip deformation in rotating disks was carried out by Azami and Nishimura [20] using the photoelasticity method and the shadowing method. They concluded that the higher the Young's modulus of the cavity inside the disk near the crack tip, the more the stress intensity factor decreases. The methods of calculating SIFs in non-isotropic materials with arbitrary geometry were studied by Banks et al. [21]. They obtained the results for a sample disk of isotropic material. Finally, they showed that the integral M method can be used as an effective and accurate method to calculate the SIFs, including the combined modes. Despite the breadth of research that has been done in this field, the simultaneous study of the effect of various parameters, such as the direction of the crack in the disk, the rotational speeds, the material of the rotating disk, and the ratio of various aspects of the crack on the fracture parameters and the opening of the crack opening under mixed mode loading has not been investigated. In rotating disks with grooves and notches, it has received less attention from previous researchers. Therefore, this article, a comprehensive study on the fracture parameters in grooved rotating disks containing three types of radial, circumferential, and inclined cracks with an angle of 45 degrees and with different aspect ratios of 0.4 to 1 in grooved rotating disks with aluminum, titanium, steel and the rotational speed of 6000 rpm to 9000 rpm has been studied under the loading conditions of the combined mode.

Equations governing the calculation of stress intensity factors in rotating disks

The most important parameters in linear elastic fracture mechanics are the stress intensity factors. These factors are a function of the geometry, loading, and boundary conditions of the problem. The first step in calculating the stress intensity coefficients is to calculate the stress contour near the crack tip. In linear elastic fracture mechanics, the stress contour near the crack tip under mixed mode loading using William's solution is expressed as follows [22]:

$$\sigma_{rr}=\frac{1}{4\sqrt{2\pi r}}[K_I\left(5\cos\frac{\theta}{2}-\cos\frac{3\theta}{2}\right) +K_{II}\left(-5\sin\frac{\theta}{2}+3\sin\frac{3\theta}{2}\right)]+T\cos^2\theta+O\left(r^{1/2}\right) \quad (1)$$

$$\sigma_{\theta\theta}=\frac{1}{4\sqrt{2\pi r}}[K_I\left(3\cos\frac{\theta}{2}+\cos\frac{3\theta}{2}\right) -K_{II}\left(3\sin\frac{\theta}{2}+3\sin\frac{3\theta}{2}\right)]+T\sin^2\theta+O\left(r^{1/2}\right) \quad (2)$$

$$\sigma_{ww}=\begin{cases}0 & (Plane\ stress)\\ \frac{8\upsilon}{4\sqrt{2\pi r}}[K_I\cos\frac{\theta}{2}- K_{II}\sin\frac{\theta}{2}]+T+O\left(r^{1/2}\right) & (Plane\ strain)\end{cases} \quad (3)$$

$$\sigma_{r\theta}=\frac{1}{4\sqrt{2\pi r}}[K_I\left(\sin\frac{\theta}{2}+\sin\frac{3\theta}{2}\right)+ K_{II}\left(\cos\frac{\theta}{2}+3\cos\frac{3\theta}{2}\right)]-T\sin\theta\cos\theta+O\left(r^{1/2}\right) \quad (4)$$

$$\sigma_{w\theta}=\frac{1}{\sqrt{2\pi r}}K_{III}\cos\frac{\theta}{2}+O\left(r^{1/2}\right) \quad (5)$$

$$\sigma_{rw}=\frac{1}{\sqrt{2\pi r}}K_{III}\sin\frac{\theta}{2}+O\left(r^{1/2}\right) \quad (6)$$

In the above relationships, r and Ө are the radial distance and angle from the crack tip shown in Figure 1. K_I, K_{II} and K_{III} represent the stress intensity factors in the first, second, and third modes, respectively. The parameter T in the above relations represents the non-singular term of stress expansion, known as T stress.

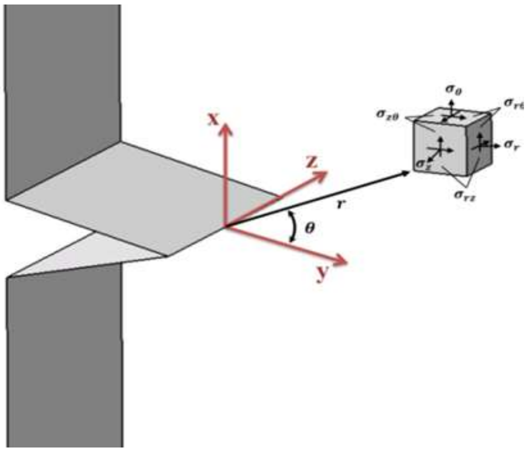

Fig. 1. A view of the crack tip coordinates

The stress values in a rotating disk without cracks can be calculated using the following equations [23]:

$$\sigma_\theta(r)=\sigma_0\left[1-\alpha\frac{r^2}{R^2}\right] \quad (7)$$

$$\sigma_r(r)=\sigma_0\left[1-\frac{r^2}{R^2}\right] \quad (8)$$

$$\sigma_0=\frac{3+\upsilon}{8}\rho\omega^2R^2 \quad (9)$$

$$\alpha=\frac{1+3\upsilon}{3+\upsilon} \quad (10)$$

where, in the above equations, R is the outer radius of the disk, υ Poisson's ratio, ρ specific mass, r inner radius, and ω is the angular velocity of the disk. For a cracked rotating disc, the SIF at each of the two ends of the semi-elliptical crack can be calculated using the following equations:

$$K_{1a}=\sigma_0\sqrt{\frac{2}{(b-a)}}\left[p_1(a)-\alpha p_2(a)\right] \quad (11)$$

$$K_{1b}=\sigma_0\sqrt{\frac{2}{(b-a)}}\left[p_1(b)-\alpha p_2(b)\right] \quad (12)$$

$$p_i(t)-\int_a^b\frac{M(t,\xi)p_i(\xi)}{\sqrt{(b-\xi)(\xi-a)}}d\xi=s_i(t) \qquad i=1,2\ ,\quad a\prec t\prec b \quad (13)$$

$$s_1(t)=\frac{a+b-2t}{2} \quad (14)$$

$$s_2(t)=\frac{1}{R^2}[\frac{t^2}{R}(a+b-2t)+\frac{(b-a)^2}{16}(a+b+2t)] \quad (15)$$

In the above equations, points a and b are considered as two crack ends. The core function $M(t,\xi)$ can also be calculated according to reference [15]. Using the Gauss-Chebyshev integral, relation (13) becomes the following form [15].

$$t_j = \frac{a+b}{2} + \frac{b-a}{2}\cos\frac{\pi(2j-1)}{2n} \quad (16)$$

The above equation represents n linear equations with n unknowns, and the unknowns are obtained by the usual methods. The calculation of p_i at both ends of the crack is also obtained according to equations (11) and (12). In these relations, it is assumed that $i = 1,\ 2$ and $j,\ k = 1,\ 2,\ ...,\ n$.

$$p_i(a) = s_i(a) + \frac{\pi}{n}\sum_{k=1}^{n} M(a,t_k)\, p_i(t_k) \quad (17)$$

$$p_i(b) = s_i(b) + \frac{\pi}{n}\sum_{k=1}^{n} M(a,t_k)\, p_i(t_k) \quad (18)$$

Therefore, stress intensity factors can be calculated using equations (17) and (18).

Description of finite element modeling of radial, circumferential, and inclined cracks in a grooved rotating disc

This part discusses the finite element modeling of grooved rotating discs with radial, circumferential, and inclined cracks. Ansys software is used for finite element modeling. The cracks generated in rotating discs are semi-elliptical and modeled in three dimensions. Three-dimensional modeling of cracks allows extraction of the values of SIFs at all points of the crack front and is much closer to the real values. In this paper, the crack in the rotating disk is studied in three different cases. Figures 2 to 4, respectively, show the schematic shape of the grooved rotating disc containing radial, circumferential, and inclined cracks with an angle of 45 degrees.

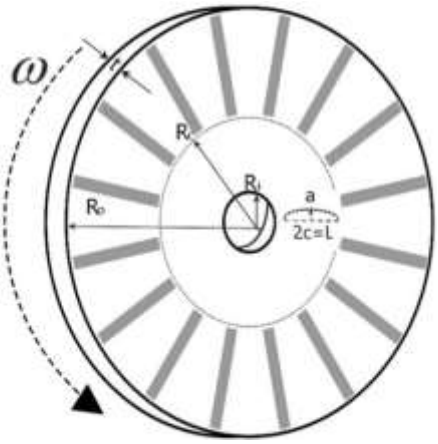

Fig. 2. Schematic figure of a radial crack in a grooved rotating disc

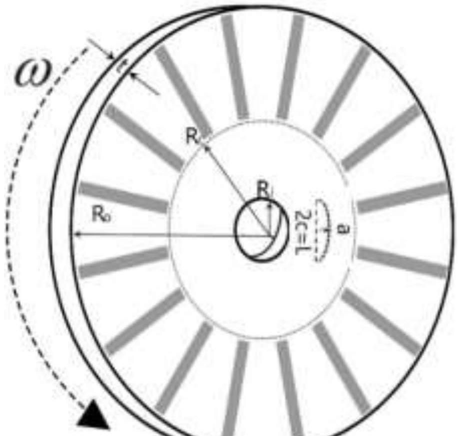

Fig. 3. Schematic figure of a circumferential crack in a grooved rotating disc

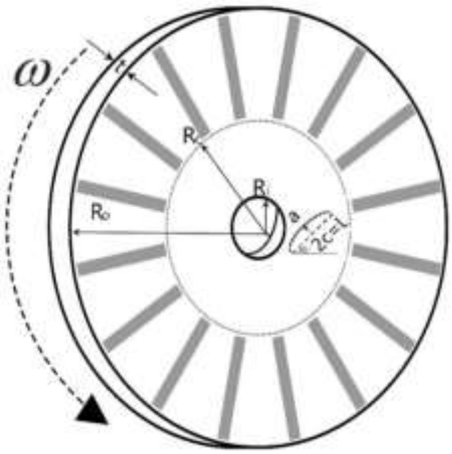

Fig. 4. Schematic figure of an inclined crack in a grooved rotating disc

The grooved disc's geometric characteristics are considered the same for all three crack modes. All three figures show a grooved rotating disc with thickness t, outer radius RO, inner radius Ri, and a semi-elliptical crack with length 2C and depth a. The length of the grooves is assumed to be L, and the distance of the crack from the center of the disc is Rc. The large diameter of the ellipse indicates the length of the crack, and the small diameter of the ellipse indicates the depth of the crack. The disc can rotate clockwise or counterclockwise with angular velocity ω. In this article, the direction of rotation of the disc is assumed to be counterclockwise. The crack plane is perpendicular to the direction of the applied tangential stress. In Table 1, the values of the parameters mentioned for the modeling of the grooved rotating disc containing the crack are given.

Table 1. Parameters considered for modeling the cracked grooved rotating disc

Parameter	Definition	Value
R_i	Inner radius of the disc	25mm
R_o	The outer radius of the disc	110mm
t	Thickness of rotating disc	10mm
R_i/R_o	Ratio of the inner radius to the outer radius	0.2
a/c	Aspect ratio	0.4,0.6,0.8,1
L	Length of the disc grooves	10mm

The singular element was used for crack meshing to simulate the singularity in the stress and strain region near the crack tip. These elements are suitable for simulating the high gradient of stress and strain in the regions around the crack. In order to determine the size and number of suitable elements for the meshing of the grooved rotating disc, the convergence of the results and the independence of the solutions with respect to the size of the element were analyzed. According to the analysis, it was observed that the maximum value of the stress intensity factor of the first mode in the grooved rotating disk has converged in the element size equal to 4 mm, and other fracture parameters are independent of the element size. Therefore, this article uses an element size of 4 mm to model grooved rotating discs with cracks under different working conditions. Figure 5 shows a view of the entire mesh of the grooved rotating disc containing a radial crack with an aspect ratio of 0.4. According to this figure, 86420 elements were used for the finite element modeling of the entire disc. Also shown in Figure 6 is the mesh around the inclined crack front with an aspect ratio of 0.6.

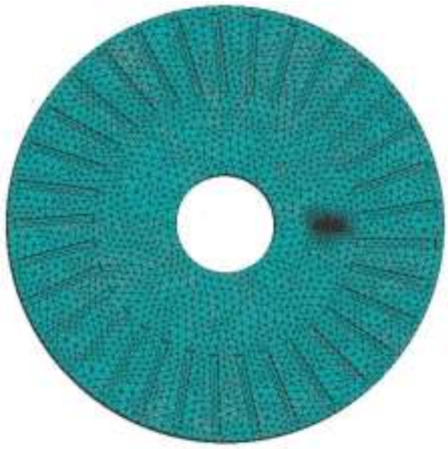

Fig. 5. A view of the meshing of the entire disc containing a radial crack with an aspect ratio of 0.4

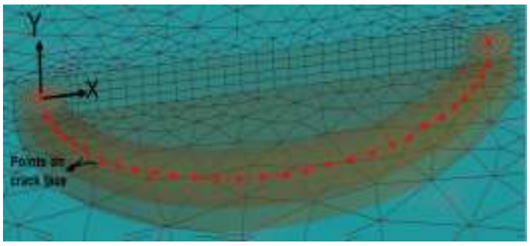

Fig. 6. A view of the inclined crack front mesh with an aspect ratio of 0.6

In order to calculate the SIFs, including the combined mode under different working conditions and to investigate the effect of different parameters on the mechanical failure behavior of grooved rotating discs, three different materials of aluminum, titanium, and steel for the rotating disc and four rotational speeds of 6000 rpm, 7000 rpm, 8000 rpm and 9000 rpm and four aspect ratios of 0.4, 0.6, 0.8 and 1 and three different crack modes are considered for the disc. The first state is the state where the disk contains a radial crack, and in the second state, the disk contains a circumferential crack, and in the third state, the crack is placed inclined with an angle of 45 degrees, so a total of 146 different states are applied to the disc in each of the states. In the disc, in the presence of the stress gradient caused by the notch and groove, SIFs are calculated and analyzed. Table 2 lists the mechanical properties of the materials used to model the grooved rotating disc.

Table 2. Mechanical properties of the materials used in the grooved rotating disc

Material	υ	$E\ (GPa)$	$\rho\left(\frac{Kg}{m^3}\right)$
steel	0.3	200	7850
aluminum	0.33	71	2770
titanium	0.36	96	4620

Verification of numerical results

In this part, in order to ensure the process of modeling and analysis of cracked rotating discs, the validity of numerical results extracted from Ansys software is discussed using the method used in this article. In this regard, the research work presented by Nami and Eskandari [24], who calculated the SIFs in a rotating blade, is used to validate the modeling and analysis process in this article. They considered a rotating steel blade and calculated the SIFs using a 3D finite element model for a circumferential crack in the mentioned blade. The geometric dimensions and properties of the materials used by Nami and Eskandari [24] are listed in Table 3.

Table 3. Geometric dimensions and properties of materials used by Nami and Eskandari [24]

Parameter	Unit	Value
Inner diameter	mm	140
Outer diameter	mm	414
Crack position (radial distance)	mm	120
thickness	mm	6
Blade rotational speed	rpm	8500
Modulus of elasticity	GPa	210
Poisson's ratio	–	0.3
density	$\left(\frac{Kg}{m^3}\right)$	7850

In order to validate the modeling and analysis process used in this article, the rotor blade considered by Nami and Eskandari [24] was modeled in the Ansys software exactly according to the specifications mentioned in Table 3, and the results of the present research are compared with the results presented by Nami and Eskandari [24]. The comparison of the results obtained using the present research method with those presented by Nami and Eskandari [24] is shown in Figure 7 for a crack with a fixed aspect ratio and different values of relative crack depth. According to this figure, it can be seen that there is a good agreement between the results of the present research and the results presented by Nami and Eskandari [24], which is valid for the modeling and analysis process used in this article.

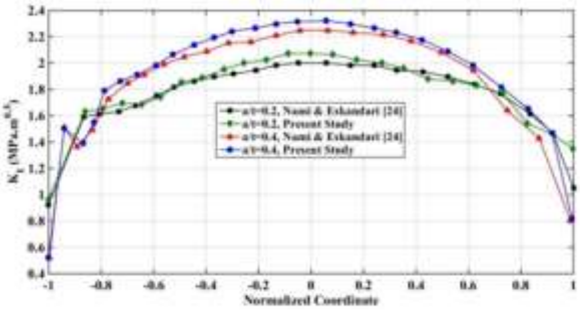

Fig. 7. Comparison of the results of the current research with the results presented by Nami and Eskandari [24]

Results

In this section, the results of the finite element analysis, including 146 different modes investigated, are presented. In order to better categorize and interpret the results, the results are presented below in the form of an investigation of the effect of various parameters such as disc material, crack aspect ratio, rotational speed, crack placement direction, and the presence of grooves on the fracture parameters and crack opening.

Investigating the effect of disc materials on stress intensity factors

Changing the material of a rotating disk affects its failure parameters due to the alteration of centrifugal force. This study examines the effect of disc material on the fracture parameters. Three materials, titanium, steel, and aluminum, are considered for the grooved rotating disc, and in each of the above cases, the values of the stress intensity coefficients are extracted in the combined mode. In the analysis conducted to compare and determine the impact of the material on the stress intensity coefficients, other variables such as the crack's aspect ratio, rotational speed, and crack placement direction have been held constant. The stress intensity coefficients for modes I, II, and III in the inclined crack front with a rotation speed of 8000 rpm and an aspect ratio of 0.6 were measured for various grooved rotating discs. The resulting diagrams can be found in Figures 8 through 10. The diagrams show that the steel rotating disc has the highest stress intensity factor values in modes I, II, and III, while the aluminum rotating disc has the lowest stress intensity factor values in the same modes.

Additionally, the change in SIF at various points of the crack front in the steel disc is greater than in the aluminum and titanium discs. Therefore, the steel rotating disc proves to be more sensitive to different points in the crack front compared to titanium and aluminum discs, with a higher percentage of variations in SIFs across various points of the crack front. The SIF diagram of the second mode shows a downward trend, unlike the first and third modes. At the midpoint of the crack, graphs of different genders intersect. This indicates that the SIF of the second mode at the midpoint of the crack is not influenced by the disc material.

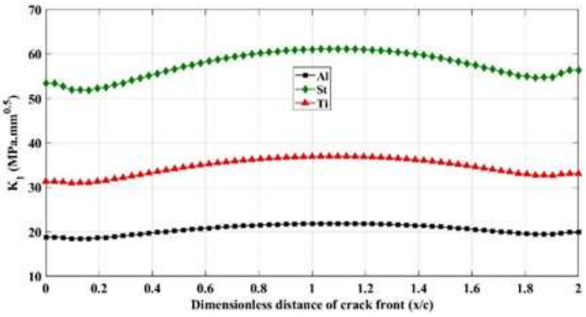

Fig. 8. Diagram of changes in the SIF k_I in the inclined crack front at a speed of 8000 rpm with an aspect ratio of 0.6 for different types of grooved rotating disc

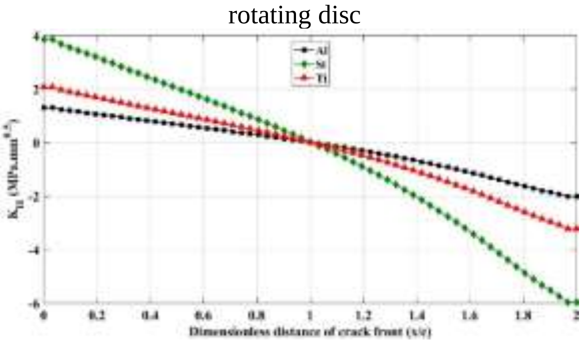

Fig. 9. Diagram of changes in SIF k_{II} in the inclined crack front at a speed of 8000 rpm with an aspect ratio of 0.6 for different types of grooved rotating disc

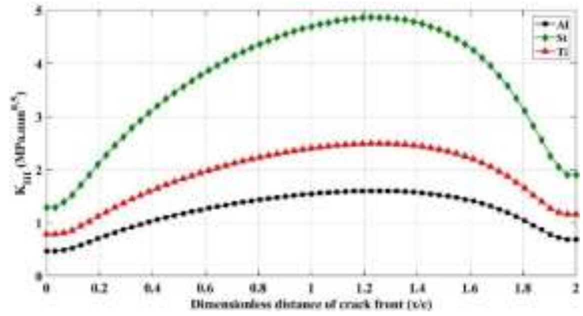

Fig. 10. Diagram of changes in SIF k_{III} in the inclined crack front at a speed of 8000 rpm with an aspect ratio of 0.6 for different types of grooved rotating disc

Investigating the effect of crack aspect ratio on stress intensity factors

Crack aspect ratio is a crucial factor that impacts failure parameters. This section investigates the effect of crack aspect ratio on fracture parameters by examining a series of semi-elliptical cracks with aspect ratios ranging from 0.4 to 1. SIFs values for these cracks have been extracted for analysis. For this purpose, we consider the crack's primary radius to have a fixed value of 5 mm and its minor radius to range from 2 to 5 mm, based on the crack aspect ratio value. We conducted analyses to compare and determine the impact of the crack aspect ratio on SIFs while maintaining fixed parameters such as disc material, rotational speed, and crack placement direction. The SIF for modes I, II, and III at the inclined crack front at a rotational speed of 6000 rpm for steel discs with different aspect ratios are shown in Figures 11 to 13, respectively. The graphs demonstrate that for cracks with a low aspect ratio of 0.4 and 0.6, where the cracks have a more semi-elliptical shape, the graph displays a concave trend. Consequently, the point of maximum value of mode I SIF occurs at the middle of the crack front. Conversely, the graph depicts a convex trend for cracks with a high aspect ratio of 0.8 and 1, where the cracks are more semicircular. This leads to the maximum value of the stress intensity factor of mode I at the crack's free surface. As the aspect ratio value decreases, the SIF also decreases. Also, the graphs demonstrate a direct relationship between the mode II SIF and the aspect ratio value prior to the midpoint of the crack front. But beyond the midpoint of the crack front, this relationship is inverted; as the aspect ratio decreases, the SIF increases until the two graphs converge at the midpoint.

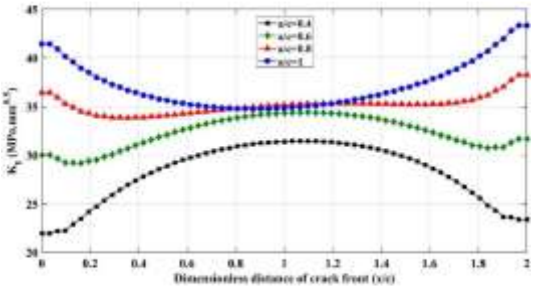

Fig. 11. Diagram of changes in SIF k_I in the inclined crack front at a speed of 6000 rpm for a rotating steel disc with different aspect ratios

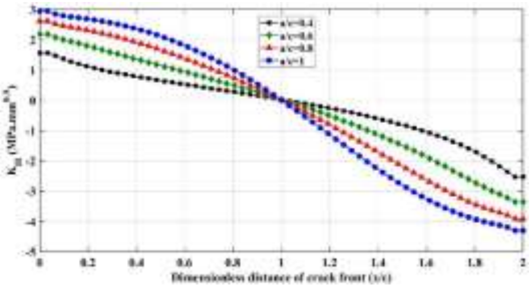

Fig. 12. Diagram of changes in SIF k_{II} in the inclined crack front at a speed of 6000 rpm for a rotating steel disc with different aspect ratios

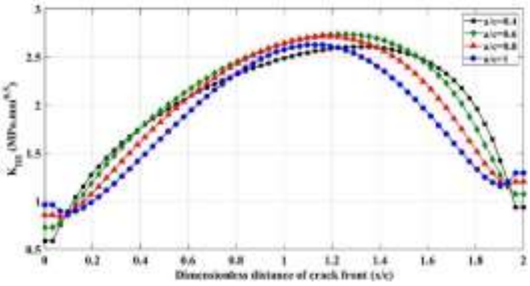

Fig. 13. Diagram of changes in the SIF k_{III} in the inclined crack front at a speed of 6000 rpm for a rotating steel disk with different aspect ratios

Another crucial factor in fracture mechanics is the stress T, which represents the non-singular term of stress expansion around the crack. A positive T stress results in increased stress around the crack tip, leading to reduced crack growth. Conversely, a negative T stress causes stress around the crack to decrease, resulting in increased crack growth. The stress diagram for the inclined crack front with a rotational speed of 6000 rpm on a steel disc with varying aspect ratios is displayed in Figure 14.

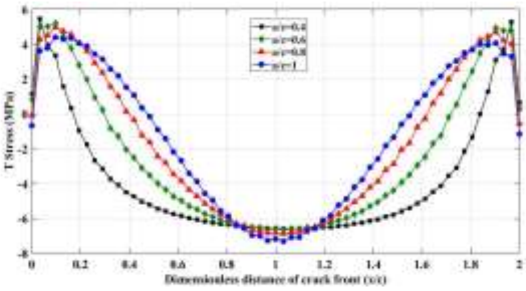

Fig. 14. The diagram of T stress changes in the inclined crack front at a speed of 6000 rpm for a rotating steel disc with different aspect ratios.

Investigating the effect of rotational speed on stress intensity factors

The rotational speed in rotating discs is the cause of the generation of centrifugal force and directly affects the failure parameters. In order to study the effect of rotational speed on failure parameters, four different rotational speeds of 6000 rpm, 7000 rpm, 8000 rpm, and 9000 rpm are considered, and the values of SIFs are extracted in each of these modes. In the analyses performed to compare and obtain the effect of rotational speed on the stress intensity coefficients of different cracks on grooved rotating discs, other parameters such as disc material and crack aspect ratio were considered as fixed. The variation diagram of mode I SIF for titanium discs with an aspect ratio of 0.4 for radial, circumferential, and inclined crack fronts with different rotational speeds is shown in Figures 15 to 17, respectively. From the figures presented, it is clear that the increase in rotational speed significantly affects the values of SIFs in different types of cracks on rotating discs. From these figures, it can be seen that as the rotational speed increases from 6000 rpm to 9000 rpm, the value of the mode I SIF in the rotating disk containing radial, circumferential, and inclined cracks increases by 124.6, 124.9, and 124.8 percent, respectively. Therefore, it can be said that a 50% increase in rotational speed causes a 125% increase in the mode I stress intensity factor regardless of the type of crack.

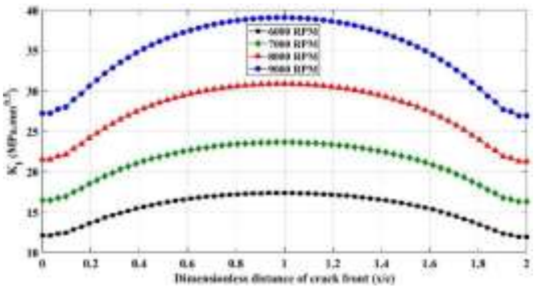

Fig. 15. Diagram of changes in the SIF k_I in the radial crack front with an aspect ratio of 0.4 for a titanium rotating disc at different speeds

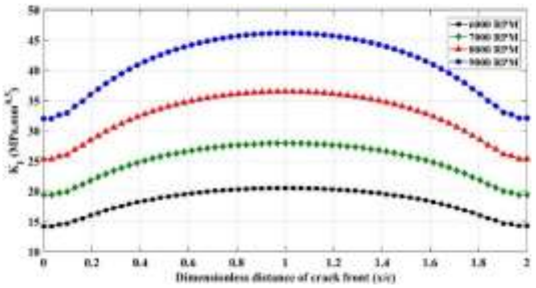

Fig. 16. Diagram of changes in SIF k_I in the circumferential crack front with an aspect ratio of 0.4 for a rotating titanium disc at different speeds

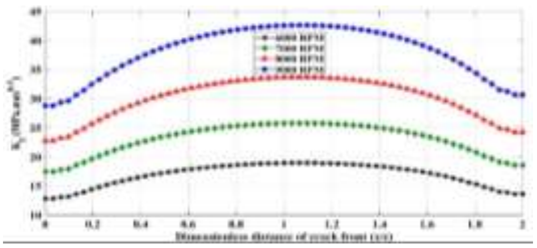

Fig. 17. Diagram of changes in SIF k_I in the inclined crack front with an aspect ratio of 0.4 for a titanium rotating disc at different speeds

Investigating the effect of crack orientation on stress intensity factors

The direction of the crack created in the rotating disk strongly affects the values of the SIFs. In this regard, in order to investigate the effect of the crack direction and also to identify the most critical type of crack inside the grooved rotating disk, three different types of cracks in the radial, circumferential, and oblique directions with an angle of 45 degrees are modeled inside the grooved rotating disc and the Mode I SIF values for different points of the crack front in these three types of cracks are extracted and compared with each other. Other parameters such as disk material, rotation speed, and aspect ratio of the crack were considered as fixed in the analyses performed to compare and obtain the effect of the crack direction on the SIFs. Figure 18 shows the variation of the Mode I SIF at a speed of 8000 rpm for a rotating aluminum disk with an aspect ratio of 0.6 for cracks with different placement directions. By comparing and checking the diagrams, it can be seen that the highest value of the SIF is associated with the grooved rotating disc with a circumferential crack, and the lowest value of the SIF is associated with the grooved rotating disc with a radial crack, and the oblique crack is located between the circumferential and radial cracks. Therefore, it can be said that the circumferential crack is known as the most critical type of crack in rotating discs. The reason is that in the circumferential crack, the load caused by the centrifugal force is exactly perpendicular to the direction of the crack and, therefore causes the maximum value of the SIF.

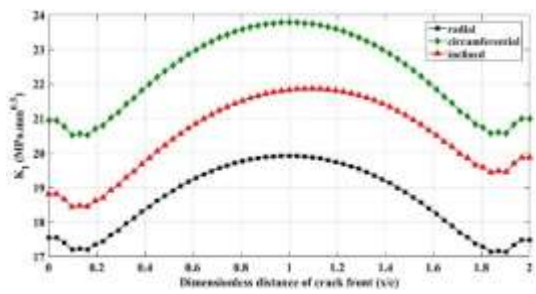

Fig. 18. Diagram of the variation of the SIF k_I with the rotational speed of 8000 rpm for an aluminum rotating disk with an aspect ratio of 0.6 for cracks with different placement directions

Investigation of crack opening

One of the important failure parameters when inspecting cracked parts is the degree of crack opening. To check the crack opening, by considering the rotation speed as 7000 rpm and, assuming steel material for the grooved rotating disk and considering the value of 0.4 for the crack aspect ratio, the crack opening parameter for three types of radial and circumferential cracks And the slope is checked with an angle of 45 degrees according to Figure 19. From the resulting figures, it is clear that the maximum opening of the crack opening is related to the circumferential crack, and the minimum is related to the radial crack. The reason is that in the circumferential crack, the load caused by the centrifugal force is exactly perpendicular to the direction of the crack and, therefore, causes the maximum opening of the crack opening.

Circumferential crack

Radial crack

Inclined crack at an angle of 45 degrees

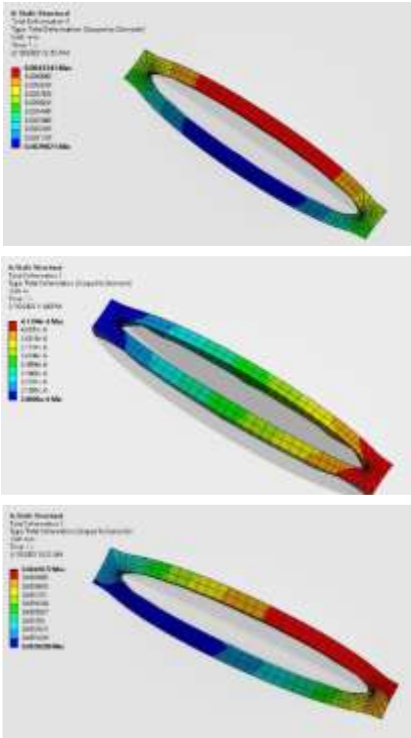

Fig. 19. A view of the crack opening in three circumferential, radial, and inclined cracks at an angle of 45 degrees.

Investigating the effect of grooves on stress intensity factor

The presence of grooves and notches causes stress concentrations and high-stress gradients in the areas around the notches, and these stress gradients can affect the stress distribution in the whole piece and cause a change in the fracture parameters of the piece. In this regard, in this part, to investigate the effect of the presence of notches on the fracture parameters, a series of circumferential cracks on the rotating disk with and without notches were modeled, and the values of the SIFs at different points of the crack front were extracted. In the analyses performed to compare and obtain the effect of the presence of grooves on the SIFs, other parameters such as disc material, rotational speed, and direction of crack placement were considered fixed. Figure 20 shows the variation of the mode I SIF in the circumferential crack front for a titanium rotating disc at 9000 rpm in the state with and without grooves for cracks with aspect ratios of 0.4 and 1. This figure shows that the presence of the groove has caused the same increase in the values of the SIF inside the rotating disc regardless of the crack aspect ratio. From this figure, it is clear that the presence of the grooves has caused an increase of approximately 8% in the values of the SIFs. The closer the cracks inside the disc are to the groove, the greater the increase in the SIFs.

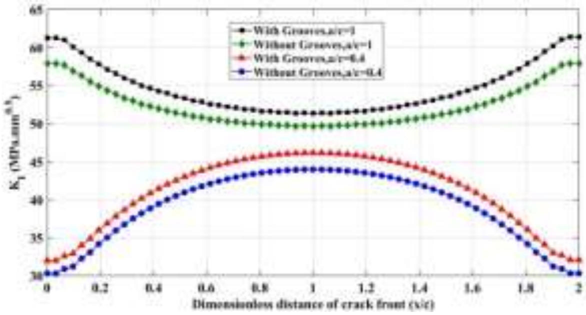

Fig. 20 Diagram of changes in the SIF k_I in the circumferential crack front for a titanium rotating disk at 9000 rpm in the grooved and ungrooved condition

Conclusion

Nowadays, the study and evaluation of the service life of rotating disks from the point of view of fracture mechanics is of great interest. Several factors, such as the presence of grooves and notches inside the rotating disc, can cause a change in the stress distribution inside the disc and subsequently change the fracture parameters. This paper has carried out a comprehensive study on the fracture parameters of cracks in rotating discs in the presence of stress gradients caused by grooves and notches. In this regard, after validating the process of modeling and analysis of cracked rotating discs, a total of 146 different modes were analyzed, and the effect of different parameters on the values of SIFs and crack opening was carefully studied and investigated. The main results of the current research can be summarized as follows:

- The rotating steel disc is more sensitive to different points of the crack front, and the percentage of changes in the SIFs at different points of the crack front in this disc is higher than that of titanium and aluminum discs.
- The second mode's SIF at the crack's center point is independent of the disc material.
- In the low aspect ratio crack (aspect ratios of 0.4 and 0.6), where the crack tends to have a semi-elliptical shape, the maximum value of the SIF of mode I occurs at the center point of the crack front, while in the high aspect ratio crack (aspect ratios of 0.8 and 1), where the crack tends to have a semicircular shape,

the maximum value of the SIF of mode I occurs at the free surface of the crack.

- The value of the Mode II SIF at the center of the crack front is independent of the crack aspect ratio value, while the value of the Mode III SIF near the beginning and end of the crack front is independent of the crack aspect ratio value.
- A 50% increase in rotational speed causes approximately a 125% increase in the mode I SIF, regardless of the type of crack.
- The maximum value of crack opening and SIF is related to the circumferential crack, and the minimum value is related to the radial crack. The opening value of the crack opening as well as the SIF related to the inclined crack is between the circumferential and radial cracks.
- The presence of grooves increases the values of SIFs by about 8%.

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