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# Fatigue Failure Analysis of Rotating Blade of Uniform Varying Cross Section with Damage at the Leading Edge

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**Abstract***:* Usually turbine blades are subjected to high centrifugal forces due to high rotational speed and also operated at highly critical environment conditions. So that the turbine blades are fail by fatigue or creep is common. High cycle fatigue (HCF) in gas turbine is one of the major problems experienced by the components of gas turbine. Since this high cycle fatigue can cause catastrophic failure this leads to damage of the blades and casing. Materials also play an important role in reducing the failure and increasing the life of the blade. Several researches are going on for the best material for gas turbines and blade materials among them nickel base single crystal is one. Nickel base single crystal material is used due to the effectiveness over polycrystalline blade materials. HCF caused by large resonance stresses is one of the main problems in turbine blade design. Fatigue analysis is done for the notched linearly varying rotating blade, the alternating stress, strain energy, stress intensity and life of the rotating blade is found. Influence of size and location of the damage on blade's life is reported. Failure analysis of the rotating blade is carried to know the effect of the notch on the damaged blade and use it in critical conditions.

***Keywords:*** Super Alloys, Single Crystal, High Cycle Fatigue, Low Cycle Fatigue, FEA

NOMENCLATURE

P = centrifugal force due to the rotational effect.

t = thickness of the plate in mm

D = width of the plate in mm.

d = width of the plate at minimum cross section in mm.

C.G = centre of gravity of the plate in mm.

e = eccentricity (distance from c .g axis to the loading axis in mm.

Z = section modulus in mm.

## I. Introduction

The major function of the turbine is to extract energy from the hot gas flow to drive the compressor and the accessory gearbox. Gas turbine blades work mostly at high temperature gradients and are subjected to high rotational velocity. High speed results in large centrifugal forces in blade and simultaneous high temperature reduces disc material strength. The service life of critical aerospace components is governed by the modes of degradation and failure such as: fatigue, fracture, yielding, creep, corrosion, erosion, wear, etc. In that fatigue is the main cause for turbine blade failure. Metals when subjected to repeated cyclic load exhibit damage by fatigue. The magnitude of stress in each cycle is not sufficient to cause failure with a single cycle [1]. Large number of cycles is therefore needed for failure by fatigue. Fatigue can be classified in to low cycle fatigue and high cycle fatigue. The main cause of turbine blade failure is high cycle fatigue. Fatigue failure is related to repeated cycling of the load on a structural member. The fatigue life of a structural member i.e. the number of load cycles it can survive is in general determined by the magnitude of the stress cycles. The exact relation between the magnitudes of the stress and the fatigue life depends on the material properties of the structural member. In general higher stresses lead to a shorter fatigue life. For some materials fatigue only occurs if stresses exceed a certain minimum level for other materials there is no minimal stress level. If the stresses that are present on the turbine blade during operation and the material properties of the turbine blade are known then an estimation of the fatigue life of the turbine blade can be made [2]. In Gas turbines, blades are usually the most critical engine components, which must endure substantial mechanical and thermal loading. Thus now a day we are using the single crystal nickel-base superalloy as the blade material. Fatigue life is enhanced by a low Young's modulus, this since the stresses will be lower for a crystal orientation with low stiffness compared to a direction with a higher stiffness when a constant strain is considered [3]. A problem arises in the turbine section it will significantly affect the whole engine function and, of course, safety of the aircraft. Excessive rotational speed of turbine is sometimes permissible for aircraft in the case of heavy operational conditions (i.e., short take off from landing ground). The joint between the turbine blade and the disc usually represents the most critical area from the point of view of the static and fatigue approaches [3], [4].

Superalloys constitute a large fraction of the materials of construction in turbine engines because of their unique combination of physical and mechanical properties. In aircraft engines, it is typical to consider density-normalized properties; thus alloy densities, which are typically in the range of 7.7–9.0 g/cm3, are of specific interest. Optimization of the relevant set of mechanical properties is of paramount importance and is dependent on a high level of control and understanding of the processes of manufacturing, because mechanical properties are a strong function of microstructure. Mechanical properties of primary interest include tensile properties, creep, fatigue, and cyclic crack growth. Depending on the details of component design, any one of these four properties may be life limiting. The super alloys are having relatively high tensile and ultimate stresses [5]. The loads associated with these regions are mainly the centrifugal forces and thermal stresses. Fatigue lives at critical points in the blade are computed using finite element stress results and the failure criterion developed.

S. Bhat and R. Patibandla[1] Metal Fatigue and Basic Theoretical Models: A Review. Basic fundamentals of fatigue failure in metal. Metals when subjected to repeated cyclic load exhibit damage by fatigue. The magnitude of stress in each cycle is not sufficient to cause failure with a single cycle. Large number of cycles is therefore needed for failure by fatigue. Fatigue manifests in the form of initiation or nucleation of a crack followed by its growth till the critical crack size of the parent metal under the operating load is reached leading to rupture.

Patil A.A., ShirsatU.M [2] Investigated the metallurgical and mechanical examinations of the failed blade. The blade was made of a nickel-base alloy Inconel 738LC. The turbine engine has been in service for about 73,500 hrs before the blade failure. Due to the blade failure, the turbine engine was damaged severely. The investigation was started with a thorough visual inspection of the turbine and the blades surfaces, followed by the fractography of the fracture surfaces, micro structural investigations, chemical analysis and hardness measurement. The observation showed that a serious pitting was occurred on the blade surfaces and there were evidences of fatigue marks in the fracture surface.

Mikael Segersäll [3] Nickel-Based Single-Crystal Superalloys. Superalloys are a group of materials that are used in high temperature applications, for example gas turbines and aero engines. Gas turbines are most commonly used for power generation, and it is only the very critical components which are exposed to the most severe conditions within the turbine, which are made from superalloy material.

Lucjan Witek[4] Failure analysis of turbine disc of an aero engine. The failure analysis of the turbine disc of an aero engine, installed in a certain type of aircraft. From the visual examination of the fractured surface, it was possible to observe beach marks, typical of fatigue failure. A non-linear finite element method was utilized to determine the stress state of the disc/blade segment under operating conditions. High stress zones were found at the region of the lower fir-tree slot, where the failure occurred. A computation was also performed with excessive rotational speed. Attention of this study is devoted to the mechanisms of damage of the turbine disc and also the critical high stress areas.

Tresa M. Pollock, Sammy Tin[5] Nickel-Based Superalloys for Advanced Turbine Engines: Chemistry, Microstructure, and Properties. The chemical, physical, and mechanical characteristics of nickel-based superalloys are reviewed with emphasis on the use of this class of materials within turbine engines. The role of major and minor alloying additions in multicomponent commercial cast and wrought superalloys is discussed. Microstructural stability and phases observed during processing and in subsequent elevated-temperature service are summarized. Processing paths and recent advances in processing are addressed. Mechanical properties and deformation mechanisms are reviewed.

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Arif Sugianto, Reza Jaya Wardhana, Nanang Yulian, I Gede Kusuma Jaya Wardana, Much tar Karokaro, Hariyati Purwaningsih[6], Failure Analysis of a First Stage High Pressure Turbine Blade in an Aero Engine Turbine on PK-GSG Boeing B747-400. The failure of a First Stage High Pressure Turbine (HPT) Blade in an Aero Engine Turbine was investigated by metallurgical investigation and stress analysis of the failed blade. The blade was made of a nickel-based superalloy.

## II. MATHEMATICAL FORMULATION

The complexity of the problem is reduced to by assuming the aerofoil section to a flat rectangular plate The rectangular plate is considered having dimension of length L = 200mm, D = 50mm and thickness t = 5mm.Estimation of the alternating stress for the Finite Width Rectangular Plate with Single Edge Semicircular notch. Here the flat rectangular bar is subjected to rotational effect. The rectangular blade is rotated with 3000 to 15000 RPM. Due to the rotational effect the blade experiences centrifugal forces. This is due to the inertia since the blade is having mass. So that the blade experiences tensile force at the tip of the blade at the same time bending stress will also affects the blade. These two forces are enough for the blade to fail and also the blade is considered with semicircular notch at the centre. Due to the notch at the centre there will be partial shifting of the centriod occurs, so small amount of bending force comes in to picture.

Equations used for converting the inertia force in to equivalent Alternating stress:

When the blade starts to rotate at the given RPM, which generates the tensile force (P) along the blade length in the radial direction [6].

The centrifugal force due to Rotational effect is given by

$$P = m_b \omega^2 R_{hub} \ldots\ldots\ldots..(1)$$

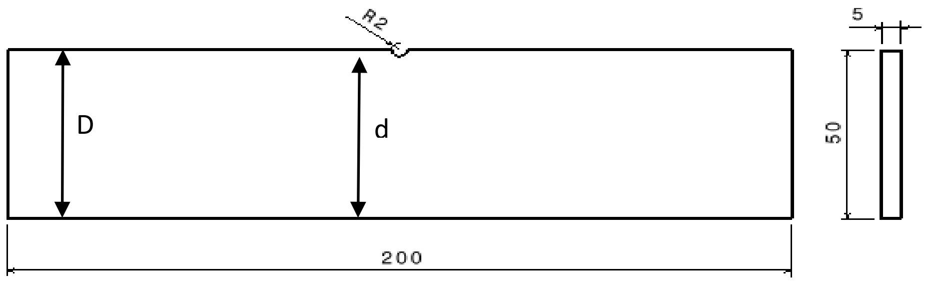


Fig 1: Flat Rectangular Plate

Now by using the equations (2) and (3) we can find the stress acting on the blade material.

$$\sigma_{nom} = \frac{P}{td} \ldots\ldots..(2)$$

$$\sigma_{nom} = \frac{P}{A} \pm \frac{M}{Z} \ldots\ldots..(3)$$

Let the load is at an eccentric distance 'e' from the x-axis. The section of the plate is subjected to direct and bending stresses. The direct stresses due to the load P is

$$\sigma_{direct} = \frac{P}{A_{min}} \ldots\ldots..(4)$$

Due to the eccentricity of the load, the section of the member is subjected to moment, M=P. e

At any distance y from the neutral axis XX or C.G, the stress intensity due to the moment M is given by

$$\sigma_{bending} = \pm \frac{M}{I} y \ldots \ldots (5)$$

Where I = moment of inertia of the section of the member about the neutral axis XX or C.G.

Where $A_{min}$= d.t and Z=I/y=td²/6

This stresses due to bending may be compressive or tensile depending on the situation of the point with respect to the neutral axis.

Hence the maximum stresses at any point distance y from the neutral axis is given by adding equation (4) + (5),

$$\sigma_{max} = \sigma_{direct} \pm \sigma_{bendimg} \ldots (6)$$

Where y is the distance from the neutral or C.G. axis and y positive above the neutral or C.G. axis and y is negative below the neutral or C.G. axis.

From the above equations we are going to get the maximum and minimum resultant stresses are found so we can calculate the alternating stresses as follows

$$s_a = \frac{\sigma_{max} - \sigma_{min}}{2} \ldots \ldots (7)$$

The alternating stress is calculated by using the above equations for corresponding centrifugal forces.

## III. FEA METHODOLOGY

FEA is numerical method. Traditionally, a branch of Solid Mechanics. Nowadays, a commonly used method for multiphysics problems. Numerical solutions to even very complicated stress problems can now be obtained routinely using FEA, and the method is so important that even introductory treatments of Mechanics of Materials. A complex problem is divided into smaller and simpler problems that can be solved by using the existing knowledge of mechanics of materials and mathematical tools. The process of dividing the model into small pieces is called meshing as shown in Fig 3a. The behavior of each element is well-known under all possible support and load scenarios. The finite element method uses elements with different shapes. Elements share common points called nodes. Here the analysis is carried out by using the properties of single crystal nickel base super alloy. Now consider single semicircular notch having the notch radius of 2mm on one side of the rectangular plate is considered having dimension of length L = 200mm, D = 50mm and thickness t = 5mm. Estimation of the alternating stress for the Finite Width Rectangular Plate with Single Edge Semicircular notch. Here the flat rectangular bar is subjected to rotational effect. The rectangular blade is rotated with 3000 to 15000 RPM. Due to the rotational effect the blade experiences centrifugal forces. This is due to the inertia since the blade is having mass. So that the blade experiences tensile force at the tip of the blade at the same time bending stress will also affects the blade. These two forces are enough for the blade to fail and also the blade is considered with semicircular notch at the centre. Due to the notch at the centre there will be partial shifting of the centriod occurs, so small amount of bending force comes in to picture. The result obtained from the ansys is compared to the theoretical results. The graph is as shown in Fig 2. In that alternating stress is plotted against the speed of the blade. From the Fig 2 we can compare the values of alternating stresses calculated from theoretical and software. There will be variation of 12% between the alternating stresses calculated from theoretical and software.

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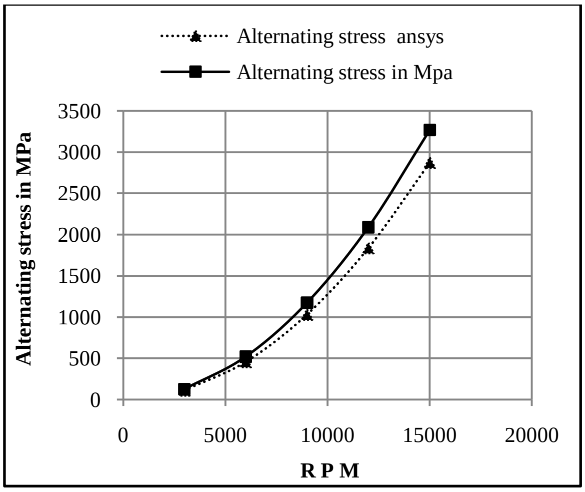
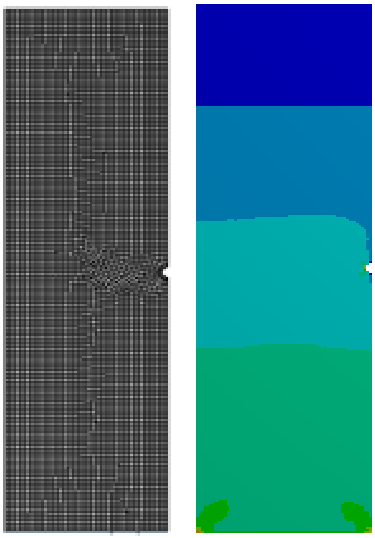



Fig 2: Variation of Alternating Stress with RPM



**(a) (b)**

**Fig 3: Meshing and Stress Patterns**

## RESULTS AND DISCUSSIONS

The dimensions of the rectangular plate taken are length 200 mm, width 50 mm and thickness 5 mm. The radius of rotation of the plate is 250 mm. The sizes of the semicircular notches are of radius 2 mm, 4 mm, 6 mm, 9 mm and 12 mm at a distance of 30 mm, 60 mm, 100 mm, 140 mm and 180 mm from the root of the blade along the leading edge of the plate. The U-notches are analyzed for a depth b = 1 mm and b = 2 mm with the same notch radius mentioned above. The plate is modeled meshed and analyzed using the ANSYS. The finite element analysis of the rectangular plate subjected to rotation of 15000 rpm is analyzed to study the fatigue analysis having the semicircular and U-notches of the blade along the leading edge of the blade.

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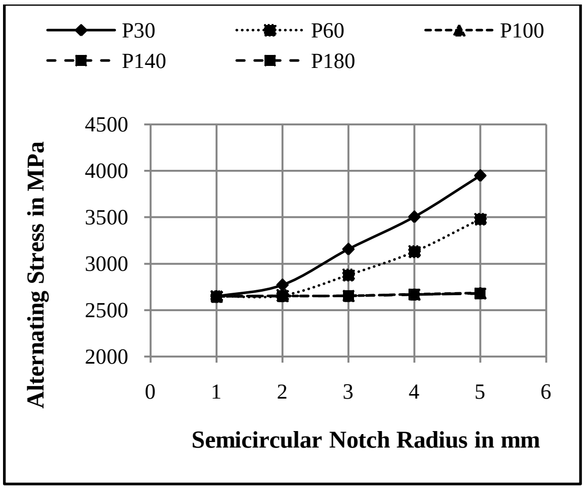
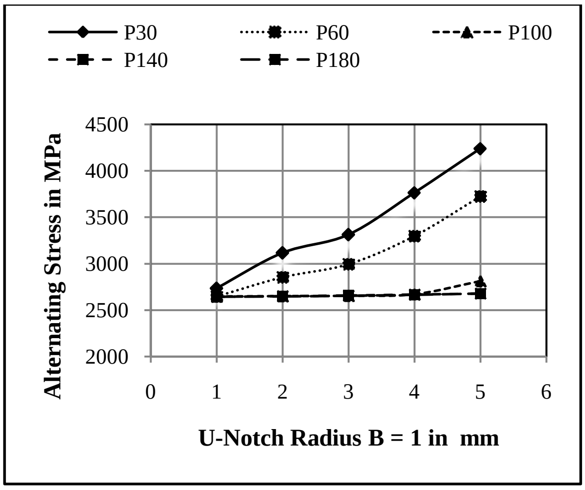
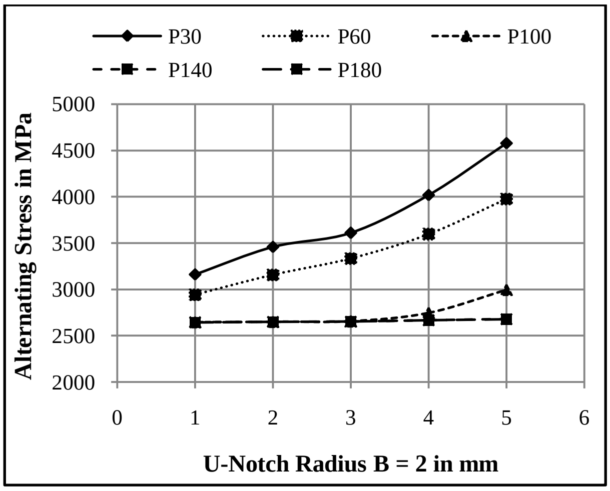
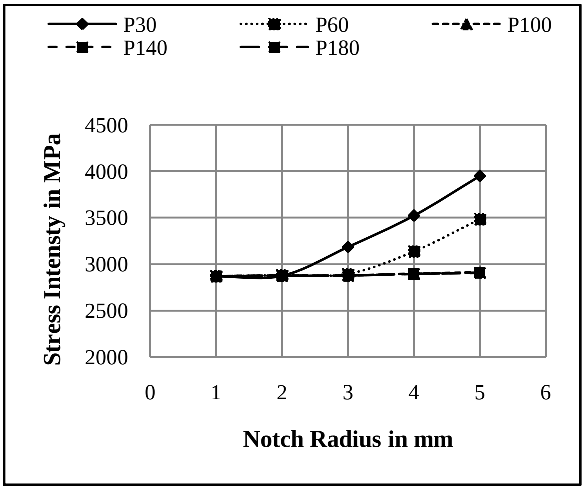



(4) (5)




(6) (7)

Fig 4: Variation of Alternating Stress with Semicircular Notch Radius for Different Position from Root of the Blade. Fig 5: Variation of Alternating Stress with U- Notch B= 1 For Different Position From Root of the Blade. Fig 6: Variation of Alternating Stress with U- Notch B= 2 For Different Position From Root of the Blade. Fig 7: Variation of Stress Intensity with Semicircular Notch Radius for Different Position from Root of the Blade.

From the results shown in the Fig 4, 5 and 6 it can observed that the stresses will be maximum as the notch radius increases at the same time the stress decreases as the notch moves from the root to tip of the blade. As the notch radius is towards the tip of the blade the stress will be almost constant irrespective of the notch radius. In Fig 4 it can be shown that the stress will be maximum when the notch is at the root and in Fig 5 and Fig 6 the stress is high compared to Fig 4 because of the notch size. When the notch radius is away from the root or the notch is towards the tip the stress is constant. From this it is evident that as the notch is present near the root the stress is maximum. From this the maintenance engineer can decide whether the damaged blade can be usable or not depending on the damage and position of the damage.

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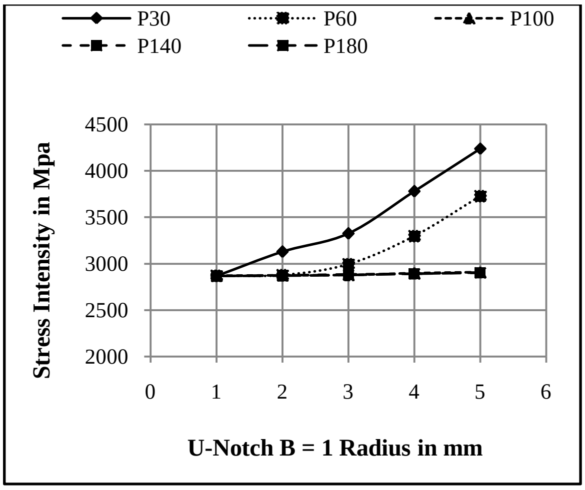


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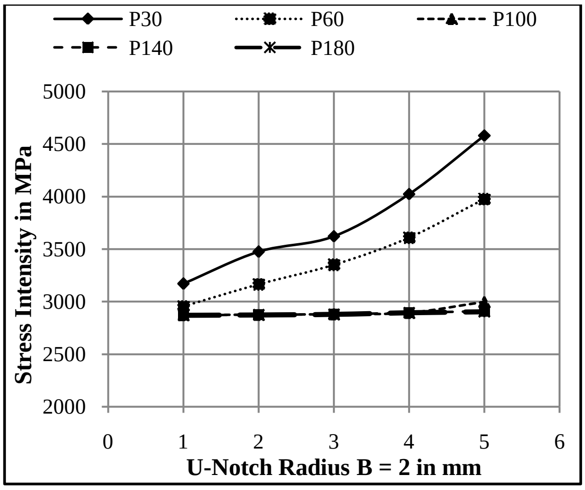


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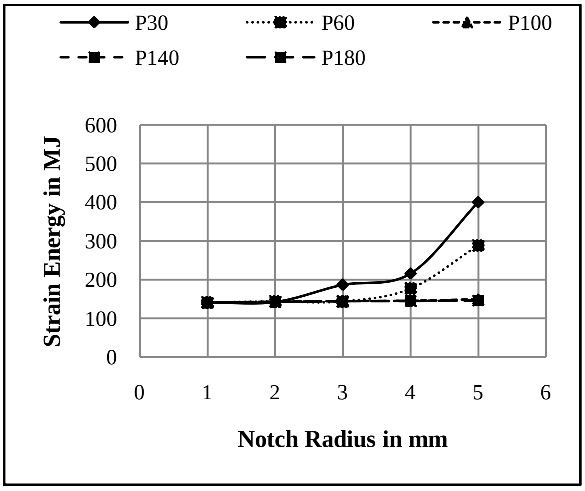


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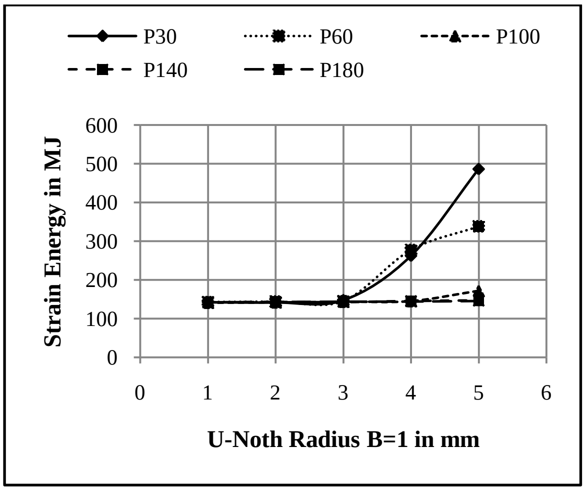


(11)

Fig 8: Variation of Stress Intensity with U - Notch B = 1 for Different Position from Root of the Blade. Fig 9: Variation of Stress Intensity with U - Notch B = 2 for Different Position from Root of the Blade. Fig 10: Variation of Strain Energy with Semicircular Notch Radius for Different Position from Root of the Blade. Fig 11: Variation of Strain Energy with U-Notch Radius B = 1 for Different Position from Root of the Blade.

Since the notches are considered at the leading edges of the linearly varying blade stress intensity plays an important role. From the above Fig 7, 8 and 9 it can be observed that it is more of similar to Alternating stress distribution. Stress intensity increases when the notch is present near the root of the blade. When the notch is near to the tip the stress intensity is constant. When the notch is semicircle the stress intensity is small and for the U-notches the stress intensity increases due to high stress concentration. Stress intensity will be almost constant for blades having the notches away from the root. By knowing the stress intensity the failure of that blade can be predicted.

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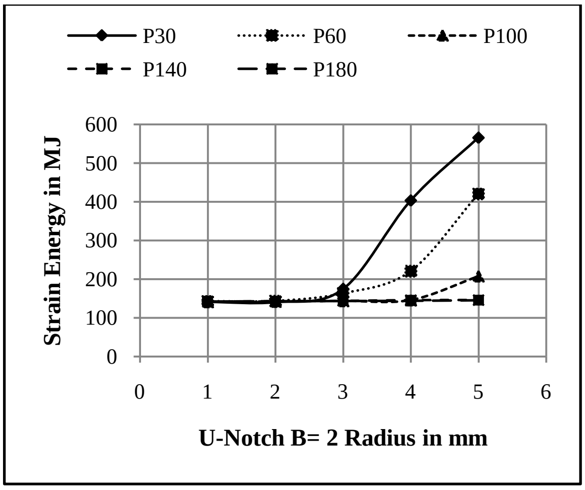


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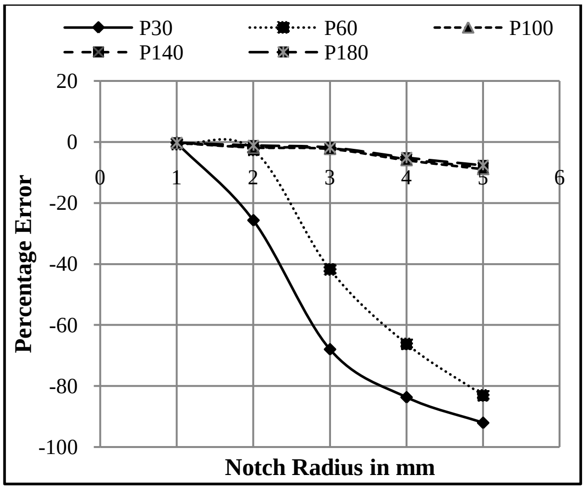


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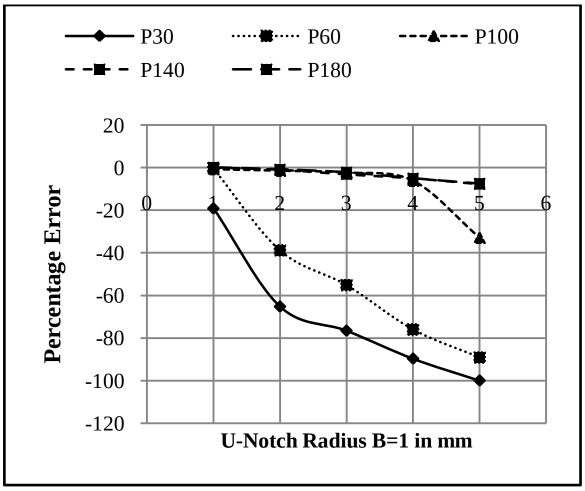


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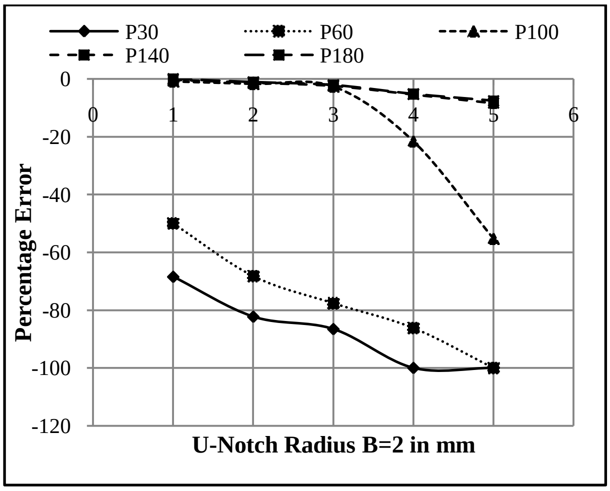


(15)

Fig 12: Variation of Strain Energy with U-Notch Radius B = 2 for Different Position from Root of the Blade. Fig 13: Variation of Percentage Error of Life with Semicircular Notch Radius for Different Position from Root of the Blade. Fig 14: Variation of Percentage Error of Life with U- Notch Radius B = 1 for Different Position from Root of the Blade. Fig 15: Variation of Percentage Error of Life with U- Notch Radius B = 2 for Different Position from Root of the Blade.

Strain energy is the energy stored in the body. Strain energy depends on the displacement and notch radius. Strain energy increases as the notch radius increases. Since as the notch radius increases displacement also increases. From the Fig 10, 11 and 12 it is clear that the strain energy is nearly constant when the notches are away from the root of the blade. Maximum strain energy can be shown at the notch radius of 12 mm which is present near the root. In Fig 11 and Fig 12 the strain energy is very high due to the increase in notch size. The strain energy depends on the maximum stress. Since the stress will be maximum for higher notch radius, strain energy is also maximum.

Life estimation is an important parameter in analyzing the failure of the blade. Comparing life of the blade with notch and without notch is made. The life of the blade without notch is having high life because there is no stress concentration due to damage. Percentage error of the life will be high the notch radius increases and when the notch is present near the root of the blade. The error will be small for the notches which are away from the root. From the Fig 13, 14 and 15 it can be concluded that the blade can be used if the damage is away from the root of the blade and also it gives the information about the damage size.

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## IV. CONCLUSION

In this study the linearly varying blade is modeled and investigated the fatigue life by considering damage at the leading edge of the blade. When the damage depth is small it can be considered as the semicircular one at the same time if the damage depth is high it is consider as U- notch. The maximum life for the blade occurs when there will be no notches on the blade. The life of the blade mainly depends on the damage and position of the damage on the blade from the root. As the damage is away from the root of the blade the life of the blade is more it can be shown from the graphs. So that we can neglect the damage which is near to the tip of the blade. In the graph results showed that the percentage variation of life increases with the notch size and its position. Percentage is very small when the notches are away from the root. Similarly the percentage is high when it is U-notch. Alternating stress and stress intensity also increases as the notch radius increases at the root at the same time Alternating stress and stress intensity are almost constant when the notch is near the tip of the blade.

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