Design and Analysis of Compressor Impeller using AL25ZN Material

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Abstract - *Since the centrifugal compressors have a wide range of applications, the reliability of impellers as the vital components should be ensured. Due to the complicated operating conditions and various Gas compositions and its corrosive and non-corrosive nature, it is important to do Finite Element Analysis (FEA) on Impeller with alternate material for its feasibility. During the operation of centrifugal compressor, failure easily occurs in the presence of stresses, cyclic loads, vibrations, corrosion. The failure process characterizes with strong nonlinearity and hence it is difficult to be described by conventional methods. On this background aim of this research was to manufacture a new Aluminium alloy Impeller in order to improve the life of an impeller. In this project, Al25Zn new aluminium material developed and found its mechanical properties. The Al25Zn has higher yield strength among its binary composition. The hardness is also higher. The addition of zinc to aluminium increases the hardness and yield strength. The new developed material properties used in stress and deformation analysis. The analysis results show that new material exhibit good properties for yield strength, stress which are less compared to steel material. This is because the stresses built are function of centrifugal forces which is mass dependent. New material has less mass compared to steel impeller as there is density variation. Identification of new material for impeller application is studied and it is observed that Standard Elastic Analysis (SEA) at initial stages helps in determining use of new material in impeller design.*

***Key Words*: Centrifugal Compressor, Impeller, Blade, Stress, Deformation, SEA, FEA, Aluminium Alloy material.**

1. INTRODUCTION

The Centrifugal impellers are widely used in various fields such as oil and gas compressors, refineries, fertilizer plants, aviation, environmental protection, CO2 injection, LNG compression, Gas pipelines and pharmacy industry. The impeller is the most essential rotating part of a radial-flow turbo compressor which imparts its kinetic energy to the fluid and increases its pressure energy. It is the heart of the compressor which is composed of hub, blades, and shrouds. Compressor performance and reliability are closely related on the impellers. The stresses developed in impeller during working of compressor are higher and construction wise also it is the most complex than for any other component on the rotating element. In view of the ever increasing importance of its performance, the geometrical design of an impeller is governed by the laws of aerodynamics, thermodynamics, and stress analysis. Generally in oil and gas application fully enclosed, Semi-open impellers are used in multistage centrifugal, single stage compressors where high efficiency and stability is required. High thermal as well as mechanical distortions are developed. Impeller stresses can be categorized by origin, type, and location. The three types of stresses which are developing during the working of impeller are steady state, thermally induced, and vibratory stresses. Due to rotation of the impeller Steady state stresses are centrifugally induced and these stresses are proportional to the square of the tip speed of the impeller. Small amount of stresses are also developed as a result of the operating gas forces. However we treat impeller as non-pressure retaining component unlike compressor case and these effects are not considered in SEA analysis. There are axial forces acting on Impeller as well. The quantum of these forces depends on stage differential pressure. These forces gets nullify over impeller eye due to same pressure on either side of impeller. Only differential pressure will act below Impeller eye area on disc side. This unbalance force is balanced with the help of balancing device on rotor. Other form of steady state stresses are induced due to the shrink fit. Shrink fit is necessary to maintain positive mounting of the impeller for torque transmissions capability. Sometimes the excessive interference may result in the high amount of compressive stresses at the impeller bore (Toe fit). Sometimes, the contact pressure may not be sufficient to hold it in that case area is increased or additional fit is provided.

Thermal stresses can be developed during the manufacturing or during the operation because of the exposure of the impeller to varying temperature, excessive speed and feed.

Perhaps the most sophisticated area of impeller stress analysis is the area of SEA. When operated away from the design conditions the centrifugal compressors Impellers may experience high amount of centrifugal stresses, which can cause a serious structural damage to impeller.

1.1. SEA ANALYSIS

The latest ANSYS 17.2 Academic Workbench introduces the concept of the project illustration. It makes a complex and multi-field analysis of physical problem to achieve its relevance through the seamless connection between the systems, avoiding the errors which are caused by data exchange between different software; the solver speed increased by 10% to 20%, reducing the solution time. Workbench is more users friendly and commands free than Mechanical APDL.

SEA gives stress results, which lets us knows the acceptability of material for particular application, if stresses built are more than yield strength, another yield strength can be selected to overcome the stresses, or operating speed to be reduced. This can be done by increasing the YS by heat treatment or using higher YS material. This paper provides the solution for alternate material.

1.2. PROBLEM DEFINITION

Development of Al25Zn material. Design and analysis of compressor impeller for low pressure application with Al25Zn developed material properties.

1.3. OBJECTIVE

1. Design and modeling of an Impeller for low pressure application.
2. Material preparation
3. Material testing and find out its Mechanical properties
4. Stress and deformations analysis of new aluminium alloy Impeller.

1.4 METHODOLOGY

1. 3-D modeling of an Impeller.
2. Material Development
3. Mechanical tests on sample bars.
4. Mechanical properties of material
5. FEA analysis of Al25Zn material Impeller and existing Impeller (steel material) for stress and deflection analysis.
6. Manufacturing of Impeller sector model.
7. Experimental investigation to validate the FEA results.

Material development flowchart as shown below:

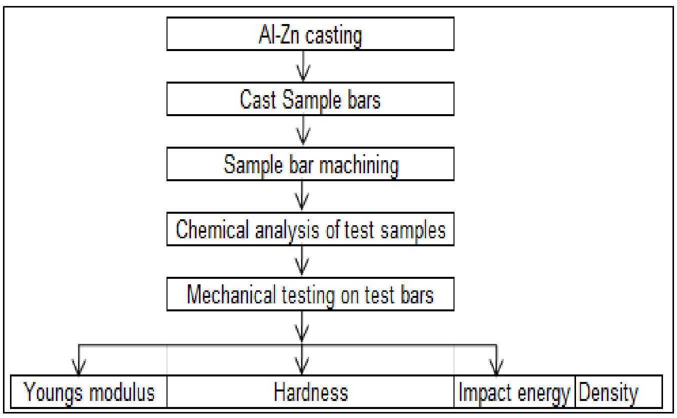


Fig 1 : Material development flowchart

SEA Flowchart as shown below :

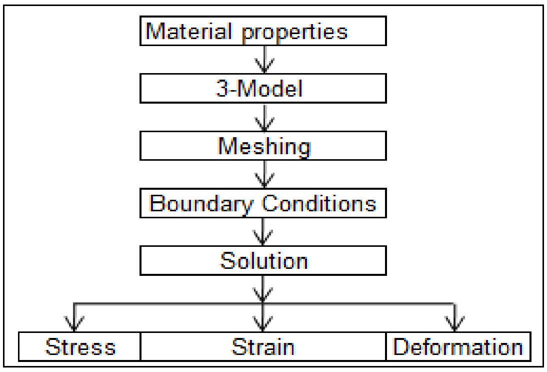


Fig 2: SEA flowchart

Impeller manufacturing flowchart as shown below:

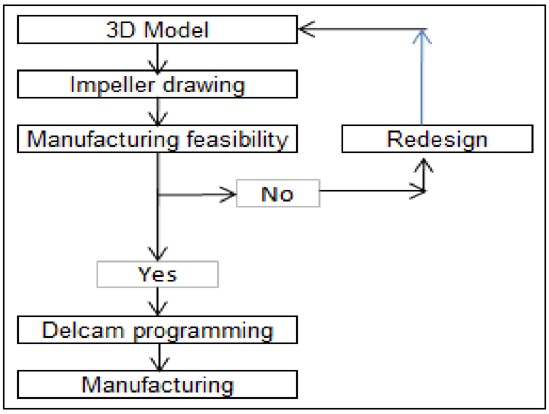


Fig 3: Manufacturing flowchart

2. Material Development

Research on material carried out. In order to develop aluminium–zinc-based a new alloy for tribo-logical applications, five binary Al–Zn were prepared by gravity sand casting. Preparation of alloys, chemical composition and microstructure of five binary Al–Zn, were prepared from commercially pure aluminium (99.7%), high purity zinc (99.9%). The density of the alloys was determined by measuring their volume and mass. The Rockwell hardness of the alloys was measured using a load of 62.5 kgf and a 2.5 mm steel ball as indenter. The tensile strengths of the alloys were measured using round specimens with a dimension 10 mm dia. and length 50mm. Young's modulus calculated based on stress and strain. The highest hardness and tensile strength were obtained with the Al–25Zn alloy among the binary ones.

(a) **(b)**

Fig 4: (a) Tensile test specimen; (b) Tensile test with Extensometer

3. EXPERIMENTAL DATA ACQUITION

Test samples prepared for Tensile test, Impact test, Hardness test and Chemical composition test as per respective test standards.

Tensile test conducted as per IS 1608 : 2005 standard.

Table 1: Tensile test data

Details	Measured	Unit
Initial Diameter	10.1	mm
Area	80.15	mm^2
Gauge length	50	mm
Yield load	21.06	KN
Ultimate load	21.12	KN
Final length	51.3	mm
Yield strength	262.75	Mpa
UTS	263.5	MPa
% Elongation	2.6	
Youngs Modlus	57.448	Gpa
Yield stress	262.75	Mpa
YS/UTS	0.997	
Final Diameter	10.02	mm

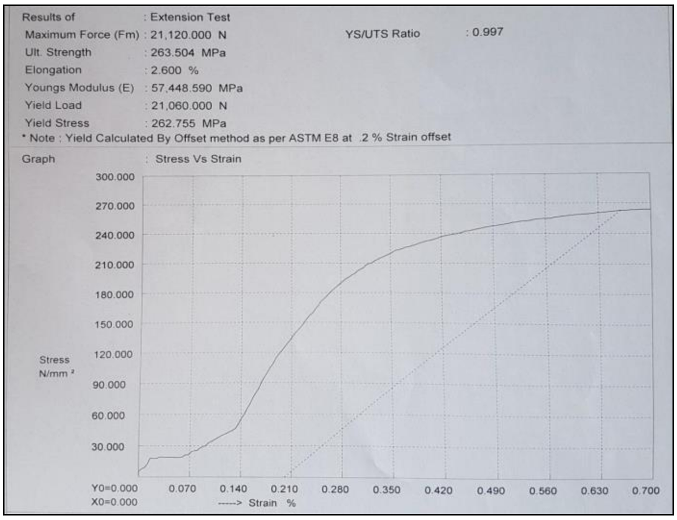


Chart -1: Stress vs Strain

Impact test conducted as per IS 1499 -2013

Table 2: Impact test results

Test no	1	2	3	Average
Impact energy (J)	4	4	4	4

Rockwell Hardness test conducted as per IS 1586 : 2012

Table 3: Hardness test results

HRBW	60	59	59

Density:

The volume of model is = 141980 mm^3 = 0.000141980 m^3
Measured mass = 425 gram = 0.425 kg.

Density = $\frac{\text{mass}}{\text{volume}}$ eq. (1)

= 0.425 / 0.000141980

Density = 2993.379349 kg/m^3

4. Mechanical Properties

Poisons ratio = $\frac{\text{lateral strain}}{\text{liner strain}}$ eq. (2)

Lateral strain = $\frac{\text{change in dia.}}{\text{original dia.}}$ eq.(3)

Linear Strain = $\frac{\text{change in length}}{\text{original length}}$ eq.(4)

Young's modulus = $\frac{\text{stress}}{\text{strain}}$ eq. (5)

Table -4: Material properties

Parameters	Observed / calculated values	Unit
U.T.S	263.5	Mpa
Young's Modulus	57448.59	Mpa
Poisson ratio	0.304645849	
Density	2993.379349	kg/m3

5. SEA OF AN IMPELLER

The latest ANSYS 17.2 Academic Workbench used for the SEA analysis of an Impeller.
Workbench uses static structural module for this Impeller analysis and steps involved are as below:

1. Engineering data- Material properties assignment
2. Geometry - Geometry definition
3. Model - Model creation / Import IGES/STP format
4. Setup - Meshing, Zero displacement surfaces, rotational velocity
5. Solution
6. Results - Min and Max. Stress, deformation at various locations.

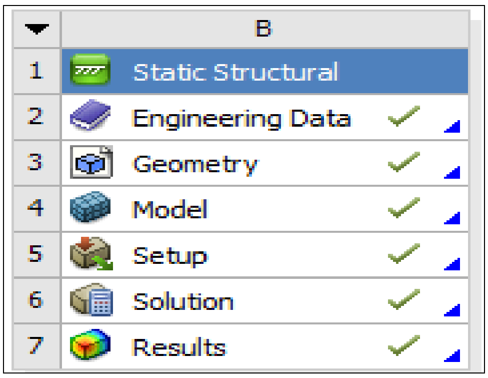


Fig -5: FEA Analysis steps.

Following mechanical properties are used for analysis

Table -5: Material properties used for analysis

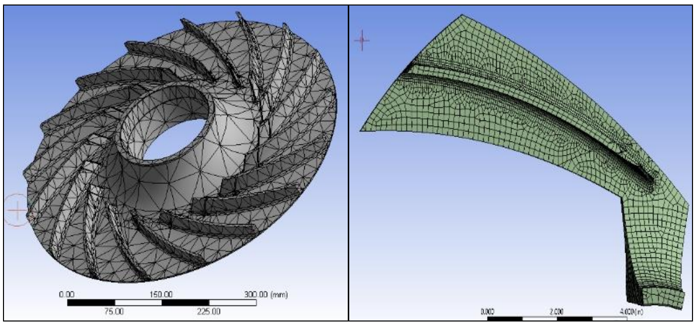
Material	Al25Zn
E, MPa	57448
Poisson' Ratio	0.3
Density, kg/m^3	3000

4.1 MODELING AND MESHING

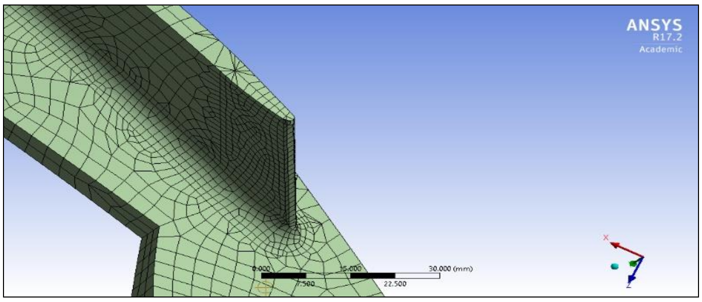
Through case study, the Impeller 3-D model created using UG-NX 8.5 according to design drawing

OD : 533.4mm
ID : 152.1mm
Blades : 17 nos

The meshing statistics are as below
Nodes: - 15589
Elements: - 30367



(a) (b)



(c)

Fig 6: (a) Impeller Meshing (b) Impeller sector Meshing (c) Meshing after topology applied on surfaces

4.2 BOUNDARY CONDITIONS AND RESULTS

Zero displacement is applied at Toe surface of impeller and on the sides of sector model as it is fized to adjacent part of an impeller.
Rotational velocity is applied as centrifugal forces are due to it.

Peripheral velocity v = πDN Eq. (6)

Angular velocity = $\frac{2\pi N}{60}$ Eq. (7)

Force = $mr\omega^2$ Eq. (8)

Stress and deflection results carried out for three iterations for following speeds, in order to find out the operating speed limit with respect to Yield strength.

Table 5: Iteration values for speed

Iteration / Time	Speed(rpm)	Velocity (m/s)	ω (rad/sec)
1	955	26.68	100
2	1800	50.28	188.5
3	2575	71.93	270

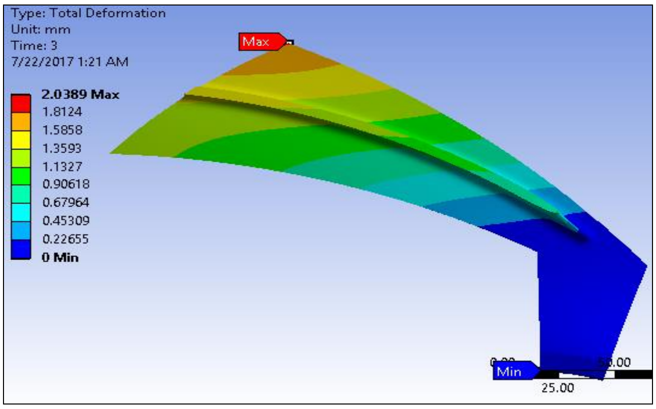


Fig.7: Total Deformation

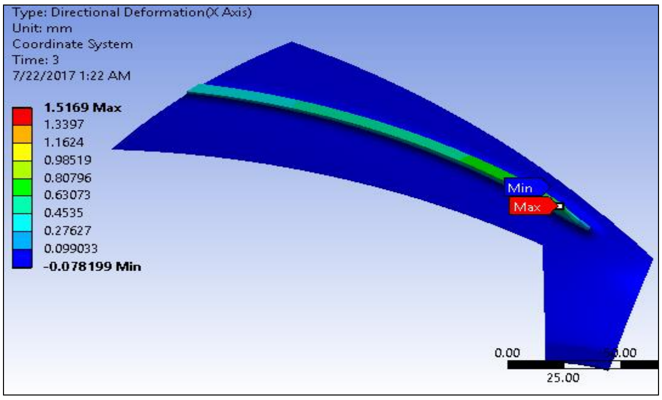


Fig.8: Directional Deformation

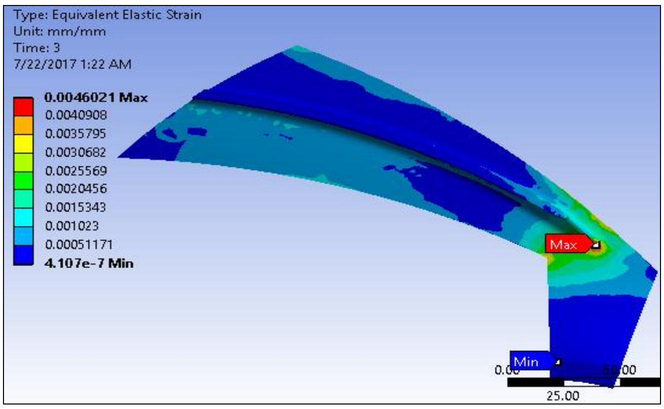


Fig.9: Equivalent Elastic Strain

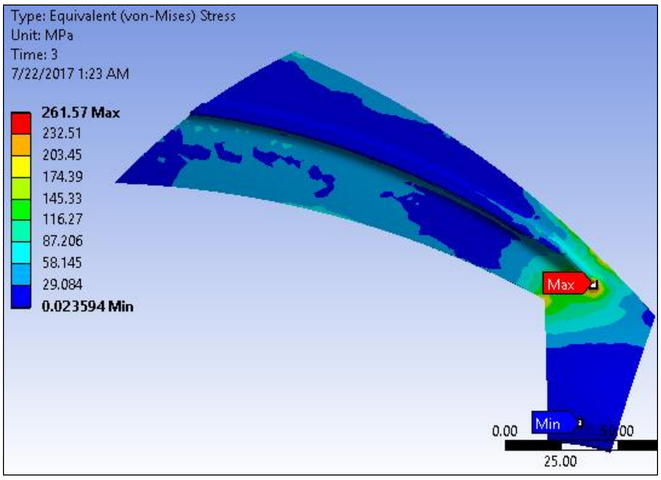


Fig.10: Equivalent Stress

6. EXPERIMENTAL VALIDATION

The tensile test samples were tested on UTM for load vs displacement and extension in order to find out the stresses and strain, Young's modulus.

Table 6 : Load vs Displacement and Extension

Loan kN	Displacement (mm)	Extension (mm)
0	0	0
3	4.494	0.0275
6	6.5	0.042
9	8	0.046
12	9.29	0.057
15	10.271	0.068
18	11	0.092
21	12.1	0.166
21.06	12.2	0.167
21.12	12.3	0.167

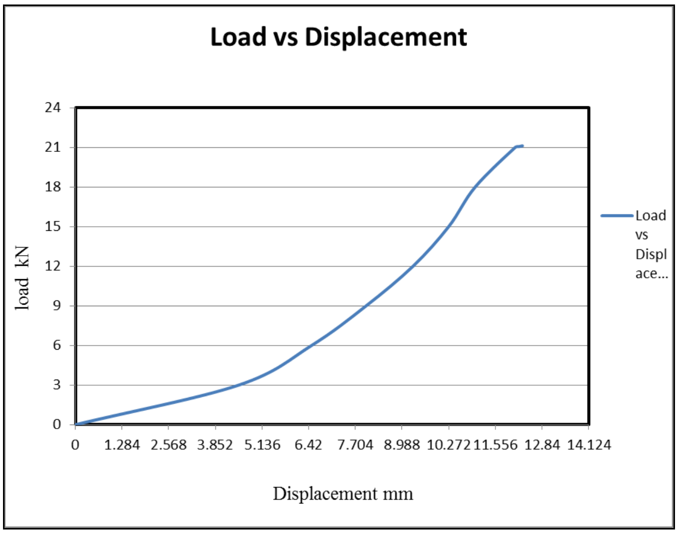


Fig.11: Load V/S Displacement

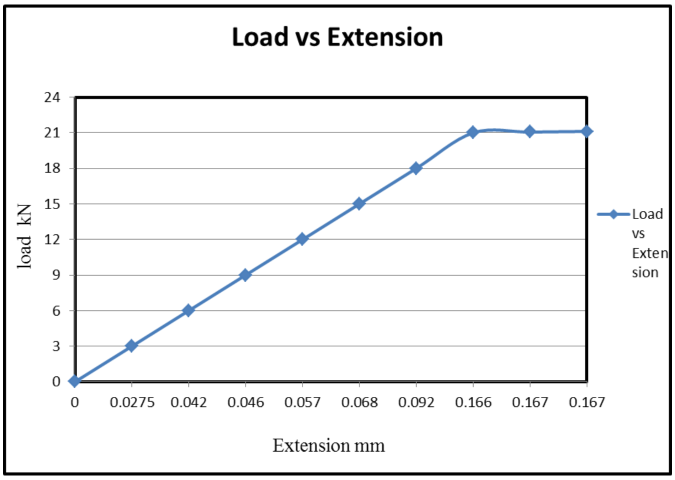


Fig.12: Load vs Extension

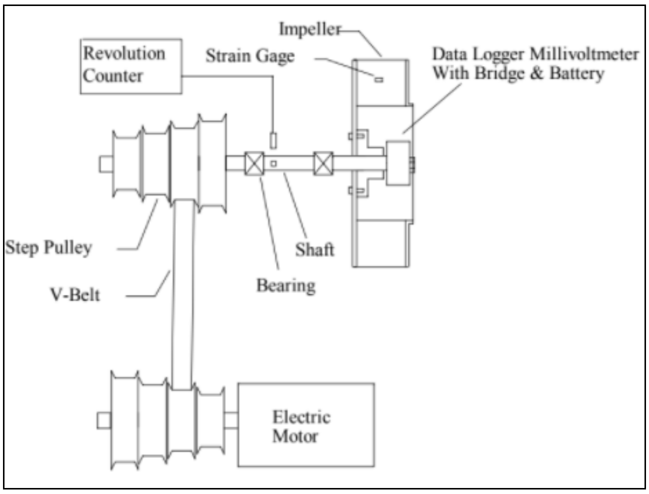


Fig.13: Experimental schematic for strain gauges on Impeller

Fig.14: Impeller sector manufactured with Al25Zn material

7. RESULTS AND DISCUSSIONS

1) The highest hardness and tensile strength were obtained with the Al–25Zn alloy among the aluminium-based binary alloys.
2) The tensile strengths of the Al–25Zn alloys increased with increasing Zn.
3) The density increased as Zinc content increases.

4) The Stress and deflection characteristics of an impeller are complex. Results of finite elements helped to understand the stresses and deformations at different locations of an impeller.
5) The stress is one the main cause of the impeller failure, and the dynamic characteristics of the impeller are not perfect because of the pitch vibration modes.
6) The deformation (in mm) at different points is as below for 1800rpm:

   At Impeller OD : 0.69
   Vane OD (top) : 0.73
   Impeller Hub Toe : 0.00018
   Impeller Hub Heel : 0.0093
   Vane ID (top) : 0.36
   Disc between vanes : 0.33
7) The equivalent stress is 123.49 MPa.
8) The selected material SEA shows that it can be used up to maximum of 2575 rpm (270 rad/sec) for selected impeller design with stress. Based on Safety Factor this rotational velocity will be reduced.
9) Results compared with steel and Al25Zn material as shown below.

Table 7: Comparison of results for Al25Zn and Steel

			Aluminium			Steel		
Sr.No	Rotational velocity	ω (rad/sec)	Stress	Strain	Total Deformation	Stress	Strain	Total Deformation
1	955	100	35.881	6.31E-04	0.279	93.888	4.74E-04	0.21
2	1800	188.5	127.49	2.24E-03	0.993	333.6	1.69E-03	0.746
3	2575	270	261.57	4.60E-03	2.038	684.44	3.46E-03	1.532

10) The above results shows that the Al25Zn has low stresses compare to Steel material.
11) We already know that the geometrical design of an impeller is governed by the laws of aerodynamics, thermodynamics and stress, because of all these consideration it's difficult to modify the impeller design though we can add addition thickness on disc outer side for its stiffness.
12) The stress due to rotation is high and can be minimized by reducing tip speed, modifying the geometry or material properties. Modifying hydraulic geometry means changing performance too which is not recommended. This can be achieved by adding the material YS by heat treatment or using different material.

8. CONCLUSIONS

1) The new developed material Al25Zn exhibits good properties for Yield strength.
2) This material had higher hardness amongst it binary composition.
3) The FEA results helped to select the appropriate material for an impeller with particular application. The selected material can be used for this impeller with up to limitation as described in results.
4) This helps to find the maximum operating range for an Impeller with given material.
5) This helps in calculating and deciding the Impeller Laby rotating clearance.
6) These results helps in giving the shrink fit of an impeller.
7) These all details are desired in design of an impeller in compressor.
8) This shows that this analysis is helpful at the initial stage of design during detail engineering.

FUTURE SCOPE

It can be another research that impeller modal frequencies can be worked out with given operating condition, material and stationery vane count details.

Also there can be another research to find out the coefficient of thermal expansion on new developed material, in order to do the thermal analysis on Impeller and check the thermal growths.

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