TOPSIS – Taguchi Analysis of Notch Parameters on the Fatigue Life of Super Duplex Stainless Steel

J. Jagadesh Kumar, G. Diwakar, V.V. Satyanarayana

Abstract: Purpose: The purpose of the current research is to quantify the impact of notch parameters viz. width, depth and central angle (perimeter length) on the fatigue life of UNS S32760 grade of super duplex stainless steel.

Design/ Methodology/ Approach: Finite element analysis approach is implemented by using the popular software package ANSYS 18.1 and the experimental runs are selected as per the requirements of Taguchi L9 orthogonal array. TOPSIS approach is used along with Taguchi method to know about the impact of notch parameters and arrive at the optimal condition.

Findings: It is quantitatively established that notch depth is the most critical parameter and it affects the fatigue life to a greater extent (63.4%) when compared to other factors viz. notch width (10.6%) and central angle (7.31%).

Keywords: Fatigue Life, Notch concentration factor, strain-life, Von-Mises stress, Closeness Coefficient.

I. INTRODUCTION

When a component is exposed to recurrent cycles of stress or strain, failure ensues by leading to fracture at some weak points and this is termed as Fatigue failure. Fatigue failure occurs by the synchronous action of cyclic stress, tensile stress, and plastic strain. The plastic strain occurring from cyclic stress initiates the crack and the tensile stress promotes the crack growth (propagation). Careful calculations of strain show that microscopic plastic strains could exist at low levels of stress where the strain might otherwise appear to be totally elastic. Though compressive stresses do not cause fatigue failure, compressive loads may induce local tensile stresses [1].

Yoshiaki Akiniwa et. al. calculated the impact of notch on fatigue strength drop of bearing steel in very high cycle regime and proved that for circumferentially notched specimens, fatigue fracture initiated from the surface or very close to the surface.

The slip deformation was the root cause for crack initiation in high cycle and very high cycle regimes. The fatigue strength of specimens with notch was less than that of smooth specimens and the extent of reduction was observed to be smaller at longer lives [2]. G.H.Majzoobi et. al. investigated the impact of notch geometry on the fatigue life of high strength and low strength steels. The results showed that the notch geometry has profound effect on fatigue life of a shaft. Three types of notch geometries, V-shape, U-shape and rectangular-shape notches of various sizes are considered for their investigation and maximum and minimum fatigue life reduction occurred for the V-shape and U-shape notches. It was further concluded that, the smaller the tip radius and open angle of notch, lower the fatigue life of shaft with a circumferential notch. Higher the depth of the notch, lower is the fatigue life due to the short propagation of the crack [3, 4]. M.Makkonen et. al. investigated the fatigue behaviour of grooved tempered steel specimens and concluded that one single method cannot predict the fatigue limit of blunt notches and sharp notches [5]. M.T.Yu et. al. investigated the fatigue behaviour of SAE 1045 steel and concluded that the fatigue notch factor increases with notch diameter for sharp notches, but it decreases with notch diameter for blunt notches [6]. Xuteng Hu et. al. studied the Effect of notch geometry on the fatigue strength of TC4 titanium alloy and concluded that notch with small radius can lead to high stress concentration and seriously reduce the HCF strength. Further, it was concluded that the notch angle and notch depth can affect the HCF strength to a certain extent [7]. G.Pluvinage proved that fatigue and fracture are not governed by the local maximum stress (or strain or strain energy density). Hot spot approach always gives an overestimation of the fracture or fatigue stress. The stress distribution exhibits a strong gradient which plays an important role [8].

In the current research, UNS S32760 super duplex stainless steel specimen without notch and specimens with different types of V-notches are evaluated under fatigue loading through finite element method (ANSYS 18.1) for a constant tensile pressure of 80 MPa. Thereafter, the pressure bearing capacity of the same specimen is evaluated with different types of notches on the surface.

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The notch geometry is changed in terms of its width, depth and the notch central angle (perimeter length). The primary objective of the research is to evaluate the impact of notch parameters on the fatigue life of UNS S32760 grade of super duplex stainless steel.

II. MATERIALS AND METHODS

2.1. Material

Super duplex stainless steel of grade UNS S32760 is undertaken for the current research due to its popular usage in marine and naval applications where components are susceptible to fatigue loading [9]. The chemical composition and mechanical properties of the material are mentioned in Table 1 and Table 2 respectively.

Table 1: Chemical Composition (wt %)

C	Si	Mn	P	S	Cr	Mo	Ni	N	W	Fe
0.03	0.8	1	0.03	0.008	24	3.00	6	0.3	0.8	Bal

Table 2: Mechanical Properties

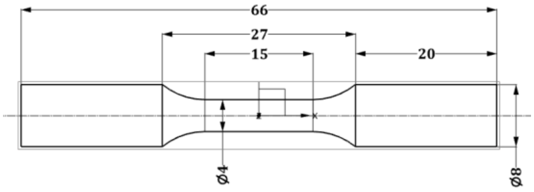
Tensile strength (MPa)	Modulus of Elasticity (GPa)	Poisson's ratio	Hardness Brinell (H_B)
898	200	0.3	290

2.2. Finite Element Fatigue Analysis

Finite Element Fatigue Analysis is conducted on the above said material using the inbuilt fatigue tool of ANSYS 18.1 package. Analysis is done for the smooth specimen as well as specimens with different types of notch geometries.

2.2.1. Specimen

The fatigue specimen as prescribed by ASTM E606 standard is modelled using CREO 3.0 and exported as IGES file to ANSYS. The drawing and the CREO model of the specimen are shown in Figure 1 and Figure 2 respectively.



(a) Standard Fatigue Specimen

(b) V-notch (c) Notch central angle

Figure 1: Fatigue Specimen and notch topology

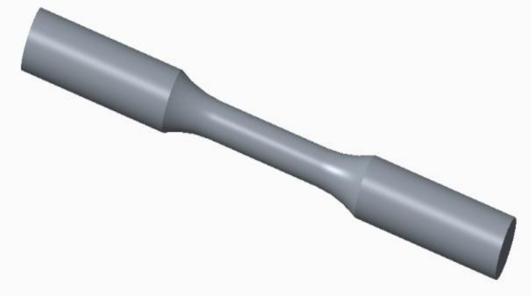


Figure 2: Solid Model created in CREO 3.0

2.2.2. Boundary Conditions

The pressure is applied as a boundary condition on the specimen and the stress induced is read from ANSYS output directly. By iteration it is found that, with a pressure of 80 MPa, the stress induced is far below the yield stress and also possessing an infinite fatigue life (> 10^6). Hence all the fatigue specimens are provided with a fixed support on the left face and a pressure of 80 MPa is applied on the right face in the direction as shown in Figure 3. Then the Von-Mises stress and fatigue life are recorded from the ANSYS output. Also, from the stress, induced at each of the notched specimen, a notch concentration factor K_t is evaluated by comparing with a smooth un-notched specimen.

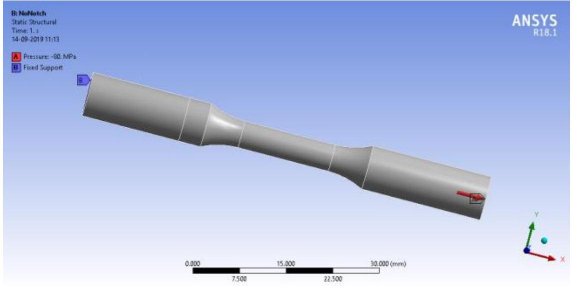


Figure 3: Boundary Conditions applied in ANSYS

2.2.3. Strain Life Approach

Strain life approach available in ANSYS 18.1 Fatigue tool is used for the current research as this approach is superior to stress life approach as far as accuracy of life prediction is concerned especially in the case of notched components. The current work makes use of Smith – Watson – Topper (SWT) approach as it gives more conservative life when compared to another available Morrow's approach.

2.3. Design of Experiments

Notches with three different factors viz. width, depth and notch central angle (perimeter length) are created on the standard specimen. Table 3 depicts the factors chosen at three levels each, in the current investigation. Taguchi L9 orthogonal array as shown in Table 4 is chosen for current investigation. Further, the 'Technique for Order of Preference by Similarity to Ideal Solution' more popularly known as TOPSIS algorithm is utilized to analyse the results. The flowchart for the TOPSIS algorithm is shown in Figure 4. The algorithm is employed in order to prioritize the output data with different weightages. The fatigue life of the notched specimens is given higher priority with 50% weightage while the other outputs viz. stress and notch concentration factor are attributed with lower priority by assigning 25% weightage each.

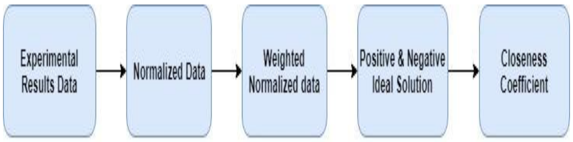


Figure 4: Flow chart for TOPSIS Algorithm

Table 3: Factors chosen and their levels

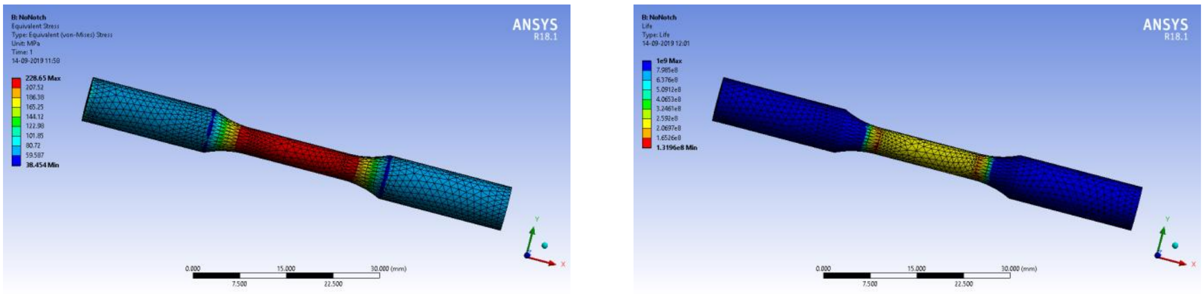
Factor	Notation	Units	Levels		
			Low	Medium	High
Width	w	mm	1	1.25	1.5
Depth	d	mm	0.5	0.75	1
Notch Central Angle	a	degrees	120^o	240^o	360^o

Table 4: Taguchi L9 orthogonal array

Taguchi orthogonal array (L9)			
Run	**Width (mm)**	**Depth (mm)**	**Notch Central Angle**
1	1	0.5	120°
2	1	0.75	240°
3	1	1	360°
4	1.25	0.5	240°
5	1.25	0.75	360°
6	1.25	1	120°
7	1.5	0.5	360°
8	1.5	0.75	120°
9	1.5	1	240°

III. RESULTS AND DISCUSSION

Static structural and Fatigue analysis is conducted for the specimen without notch and the other nine specimens with different types of notches as per the L9 orthogonal array of Taguchi Design of experiments. Table 5 and Table 6 depict the results of the specimen without notch and the specimens with different types of notches respectively. Figure 5 shows the results of the specimen without notch while Figure 6 shows the results of a typical experiment (Run 9) of the L9 orthogonal array and are obtained from the ANSYS output. The computed notch concentration factor is also included in the results (Table 6). The material employed in the investigation consists of high amounts of Chromium and Molybdenum which induces greater strength along with superior corrosion resistance [1]. Hence it is exhibiting an infinite fatigue life even at high stress induced in the material (Table 5). For the specimens which are grooved with notches, the fatigue life has reduced and the stress induced has increased due to reduction in cross-sectional area. But the diversity in variation of them is different owing to the kind of notch created on the specimen. The fatigue life is highest when the notch width is 1.5 mm and depth is 0.5 mm with a length on the circumference measured in terms of notch central angle of 360°, while it is the lowest when notch width and depth are changed to 1.25 mm and 0.75 mm respectively at the same notch central angle.

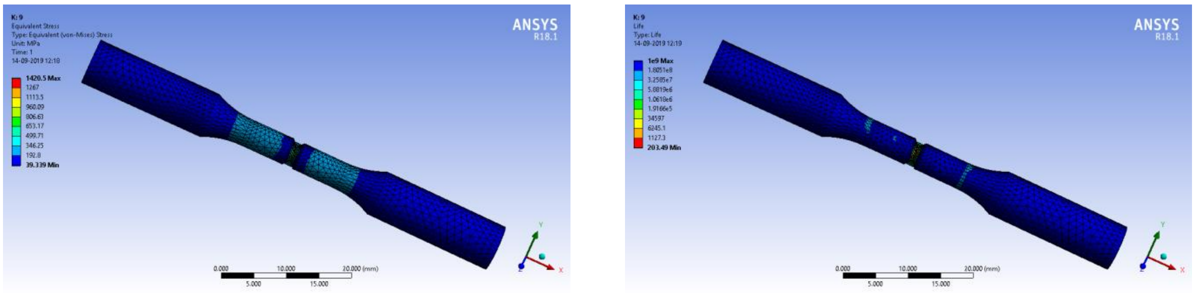


(a) Von-Mises Stress (b) Fatigue Life in cycles

Figure 5: Results of Specimen without notch

Table 5: Results of the specimen without notch

Von-Mises (Equivalent) Stress (MPa)	Fatigue Life (cycles)
228.65	Infinite (> 10^6)



(a) Von-Mises Stress (b) Fatigue Life in cycles

Figure 6: Results of Specimen used for run 9

Table 6: Results of the specimens with different types of notches

Run	Width (mm)	Depth (mm)	Notch Central Angle (degrees)	Von-Mises Stress (MPa)	Fatigue Life (cycles)	Notch Concentration Factor K_t
1	1	0.5	120^o	757.15	2733	3.31
2	1	0.75	240^o	1101.1	509	4.82
3	1	1	360^o	1092.6	525	4.78
4	1.25	0.5	240^o	772.93	2452	3.38
5	1.25	0.75	360^o	1587.9	141	6.95
6	1.25	1	120^o	911.18	1113	3.99
7	1.5	0.5	360^o	705.64	4033	3.09
8	1.5	0.75	120^o	1310.4	275	5.73
9	1.5	1	240^o	1420	203	6.21

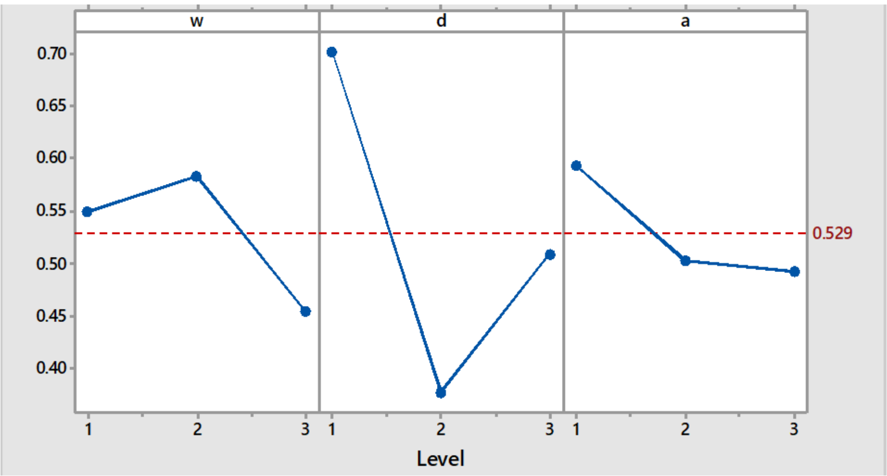


Figure 7: Closeness Coefficient (vs) Factors

Table 7: Closeness coefficients evaluated from TOPSIS algorithm

Run	Von-Mises Stress (MPa)	Notch concentration factor, K_t	Fatigue Life (cycles)	Normalized Data			Weighted Normalized Data			Ideal Solution		Closeness Coefficient
				Stress	K_t	Fatigue Life	Stress	K_t	Fatigue Life	Positive	Negative	
1	757.15	3.311	2733	0.267	0.001	0.964	0.067	0.000	0.482	0.183	0.438	0.706
2	1101.1	4.816	509	0.908	0.004	0.420	0.227	0.001	0.210	0.284	0.247	0.466
3	1092.6	4.778	525	0.901	0.004	0.433	0.225	0.001	0.217	0.277	0.251	0.475
4	772.93	3.380	2452	0.301	0.001	0.954	0.075	0.000	0.477	0.175	0.434	0.713
5	1587.9	6.945	141	0.996	0.004	0.088	0.249	0.001	0.044	0.448	0.206	0.315
6	911.18	3.985	1113	0.633	0.003	0.774	0.158	0.001	0.387	0.139	0.362	0.722
7	705.64	3.086	4033	0.172	0.001	0.985	0.043	0.000	0.493	0.206	0.448	0.685
8	1310.4	5.731	275	0.979	0.004	0.205	0.245	0.001	0.103	0.390	0.210	0.350
9	1420	6.210	203	0.990	0.004	0.142	0.247	0.001	0.071	0.422	0.206	0.328

Table 8: Analysis of Means (ANOM)

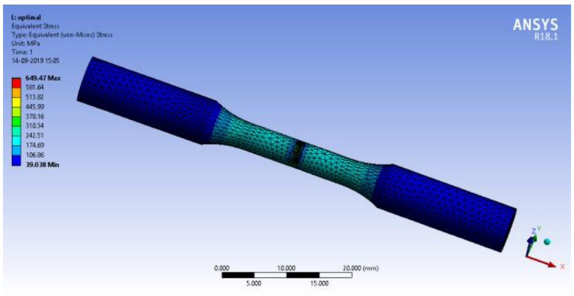
Parameter	Level 1	Level 2	Level 3	Range	Rank
w	0.549	0.583	0.454	0.129	2
d	0.701	0.377	0.508	0.325	1
a	0.593	0.502	0.492	0.101	3

Table 9: Analysis of Variance (ANOVA)

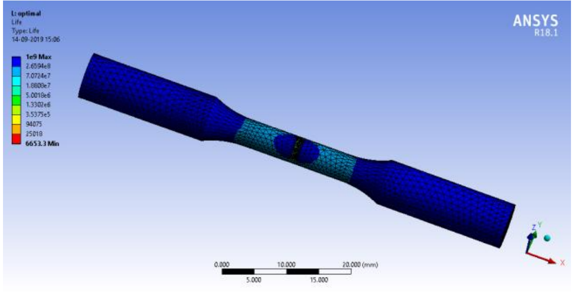
Source	DOF	SS	MS	F-Value	% Contribution
w	2	0.02670	0.013350	0.57	10.60
d	2	0.15984	0.079920	3.40	63.44
a	2	0.01843	0.009215	0.39	7.31
SSE	2	0.04698	0.023490		
SST	8	0.25195			

Table 10: Optimal Parameter Condition

w	d	a
Level 2	Level 1	Level 1



(a) Von-Mises stress



(b) Fatigue Life

Figure 8: Confirmation experiment at optimal parameter condition

Table 11: Optimal output

Von-Mises Stress (MPa)	K_t	Fatigue Life (cycles)
649.47	2.84	6653

The stress induced is the highest to an extent of 1587.9 MPa and the fatigue life is at the lowest ebb (141 cycles), while the stress is lowest at 705.64 MPa with a largest fatigue life of 4033 cycles and is in consonance with the mechanical properties of all other ferrous materials [10]. The notch concentration factor has increased with the increase of notch width and depth. It is observed that, higher the notch concentration factor, lower is the fatigue life of the specimen and vice-versa; this result is also in tandem with the materials when those are subjected to static and fluctuating loads [11].

In multiple response situations, compensatory methods like TOPSIS allow trade-off between criteria, where a poor result in one criterion may be neglected by a good result in another criterion, provides a realistic form of modelling and hence normalization is performed with weights [12, 13]. The weighted normalized data and the closeness coefficients computed for each of the experimental runs have been illustrated in Table 7. The closeness coefficients have been subjected to analysis of means (Table 8) and analysis of variance (Table 9) as per the guidelines of Taguchi method. The graphical representation of ANOM results have been presented in Figure 7. The notch depth has been playing the major role (rank 1) with a contribution of 63.44% in governing all the responses while the notch central angle exhibits least role (rank 3) with a contribution of 7.31%. The width of the notch is occupying the intermediary role in effecting the responses. 'Higher-the-better' criterion of Taguchi is employed and optimal parameter condition is drawn from the analysed data and is enlisted in Table 10. The predicted optimal value is given by the equation; $m + \sum_{i=1}^{n}(m_i - m)$, where m is overall mean of closeness coefficients and m_i is the mean of i^{th} parameter at optimal condition. The predicted optimal closeness coefficient is 0.819 and the closeness coefficient obtained by performing the confirmation experiment (Figure 8) at optimal parameter condition, is found to be 0.669. The optimal output so obtained is presented in Table 11 and an optimal fatigue life of 6653 cycles can be achieved if the component is subjected to a stress of 649.47 MPa with a notch concentration factor if 2.84.

IV. CONCLUSIONS

- The notch depth is critical and it affects the fatigue life more (63.4%) when compared to other factors viz. notch width (10.6%) and central angle (7.31%).
- TOPSIS-Taguchi method has rationally identified the effect of parameters on the responses.
- The stress and notch concentration factors evaluated in the investigation provide data for the design of members subjected to fluctuating loads.

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ABBREVIATIONS

TOPSIS	:	Technique for Order of Preference By Similarity to Ideal Solution
OA	:	Orthogonal Array
ANOM	:	Analysis of Means
ANOVA	:	Analysis of Variance
SWT	:	Smith – Watson – Topper

AUTHOR PROFILE

J. Jagadesh Kumar is pursuing doctoral degree in the field of mechanical engineering under the esteemed guidance of the second and third authors. His research interests include Fatigue analysis of metals, Finite element analysis, design optimization and allied fields.