NUMERICAL AND EXPERIMENTAL FRACTURE MECHANICS BASED OPTIMISATION OF SPECIMEN AND NOTCH PARAMETERS OF AA-5052 ALLOY

C N ABISHYAM[1], Anurag MISHRA[2], D KARTHIK[3], Manoj KUMAR K K [4] and C.S SUMESH[5]

[1,2,3,4,5] Dept. of Mechanical Engineering, Amrita school of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India.

[1]E-mail: abishyam2@gmail.com, [2]E-mail: anurag199724@gmail.com, [3]E-mail: karthikdeva001@gmail.com, [4]E-mail: manojkumar22898@gmail.com, [5]E-mail:cs_sumesh@cb.amrita.edu

***ABSTRACT**: The major aim of the present paper is to evaluate the J integral of thin ductile sheets and to examine the significance of the measured J integral, to explain the fracture resistance of AA 5052 sheets. Notch Tip Opening Displacement (NTOD), Max. Load, Failure Load, and J integral were considered as response parameters. Specimen thickness, Specimen Width and Notch Length to Width ratio were considered as design parameters. Single Edged Notched Tension (SENT) specimens were prepared as per ASTM E1820 standards and tested in UTM under Mode I loading. Later a numerical model of SENT specimen was developed to determine the J integral and model was validated with the NTOD experimental results. The optimum values of the design parameters are found using Response Surface Methodology (RSM). It was found that, the specimen thickness and width have significant influence on all response parameters.*

***KEYWORDS**: NTOD, SENT, J integral, Response Surface Methodology, ANOVA, Multi Objective Optimization*

1 INTRODUCTION

Thin sheets of metals are most commonly used in bridges, aircrafts, ground vehicles, pressure vessels, naval architecture, etc. The fracture toughness of these sheets is known to be significantly larger than the plane strain toughness of thick sheets under Mode I loading. So, this fracture toughness value is important in many applications. However, it is very hard to determine the fracture toughness of thin sheets as their specimen tends to buckle during testing (P. S. Shinde et. al. 2012).

Aluminium 5052 alloy finds wide range of applications in aircraft, pressure vessels and other structural applications. It is having highest strength compared to other non-heat-treatable alloys. The use of Al alloy for structural components, depends on the values of various mechanical properties. One of these major properties is fracture toughness, ie. ability of the material, with crack, to resist fracture.

Table 1: Chemical composition of AA 5086 (Shanavas S and Edwin Raja Dhas, 2017)

Component	Percentage Weight
Cr	0.18
Cu	0.01
Fe	0.29
Mg	2.33
Mn	0.08
Si	0.14
Ti	0.02
Al	Balance

G.B.Manjunath et. al (G.B.Manjunath et. al 2015) investigated the fracture behaviour of composite, made of jute and epoxy resin, having different notch values. Also, used ANOVA and RSM to determine the most significant factor. (Prakash Chandra Gope et al. 2014) The existence of cracks, leads to propagation of cracks and finally fracture of materials. But it is enormously hard to produce defect free materials. Hence, during the service, cracks are introduced to understand the ability to resist crack and it is very essential. The important properties are better toughness and crack resistance. S. V. Adiban and Dr. M. Ramu (S. V. Adiban and Dr. M. Ramu 2018) investigated the effect of crack types, crack position, element size on fatigue life of welded structures under constant cyclic loading using XFEM in Abaqus software. (J.O. Oji et al. 2014) Analysis of Variance (ANOVA) was performed on the data collected from the RSM design of experiments. It can be used to identify set of values of parameters which will optimize the process.

G.B.Manjunath et. al (G.B.Manjunath et. al 2015) studied the fracture behaviour of Single Edge Notched Bend (SENB) specimen made of jute reinforced epoxy composite using Taguchi method. The most influencing parameter was estimated using RSM and regression analysis. S. Doddamani and M. Kaleemulla (S. Doddamani and M.Kaleemulla,2019) presented the study of fracture behaviour of composite made of Al6061 with graphite, using stir casting technique. Taguchi method was used to optimize the compact tension specimen parameters. (Anderson T.L., 2013) Energy release rate, J integral and the crack tip opening displacement are the most important fracture mechanics parameters. Many experimental techniques have been developed to measure these parameters. Toshiyuki Meshii et. al. (Toshiyuki Meshii et. al. 2010, 2013, 2015) describes, the effect of specimen thickness on fracture toughness of compact tension specimens. Marco Palombo et. al. (Marco P., 2015) performed CTOD tests, on SENB specimens made of carbon steel, to find a correlation between CTOD, toughness and thickness of specimen. Raviraj M. S. et. al. (Raviraj M. S., 2016) investigated fracture characteristics of CT specimens, made of Al6061 – TiC particles, having different specimen parameters. In order to estimate the fracture toughness of specimens, a load vs CTOD graph was plotted for different thickness. Zamani P. et. al. (Zamani P., Jaamialahmadi A., Shariati M., 2016) developed a 3D finite element model to determine the influence of crack depth, position of crack, inside pressure, pipe thickness and crack length on design of safety of pipes used in petroleum and gas industries.

(Rajan, B et. al. 2018) RSM is a suitable method for optimization and has the advantages of reduced number of experimental runs, cost effective and saves a lot of time. R. B. Kiran et. al. (R. B. Kiran et. al. 2018) investigated the influence of residual stress, crack length to width ratio of specimen and Poisson’s ratio on the stress intensity factor using a numerical analysis. Shahani A R et. al. (A.R. Shahani 2010) experimentally investigated the influence of specimen thickness on fracture toughness of CT specimens made of steel alloy. The specimens are prepared as per ASTM E813 standards. C. S. Sumesh and P. J. Arun Narayanan (C. S. Sumesh, P. J. Arun Narayanan 2018) Studied the effect of notch depth to width ratio on critical load and J integral of U notched specimens made of Al 8011 alloy. Also plotted the failure assessment diagrams to find the safe load and studied the failure mechanisms of the specimens.

The ductile fracture mechanisms, which includes crack initiation and propagation, in X42 grade steel was compared using XFEM with experimental results from SENT specimens (Iman Ameli et. al. 2019). (Dong-Yeob Park and Jean-Philippe Gravel 2015) experimentally compared the CTOD from geometry and J integral conversion, using ASTM E1820 and double clip gauge method techniques on SE(B). D M Kulkarni et. al. (Kulkarni, D.M et. al. 2004) investigated the validity of fracture parameter J integral and determined critical CTOD using J – CTOD relation, in CT specimens made of EDD steel sheets.

YifanHuang and WenxingZhou (YifanHuang, WenxingZhou 2020) investigated the effect of residual stresses on J integral at the crack front, using 3D finite element model of clamped SENT specimens. In this analysis, shallow and deep cracked specimens are considered. Xian-Kui Zhu et. al. (Xian-Kui Zhu et. al. 2017) compared CTOD – R curve testing methods for SENT specimens, in the clamped conditions. Also, in this study, different J-conversion methods and double clip gage methods are evaluated. A.R.Torabi et. al. (A.R.Torabi et. al. 2019) determined the notch stress intensity factor for sharp V notched SENT and SENB specimens, subjected to Mode I loading, using digital image correlation. D.Frómeta et. al. (D.Frómeta et. al. 2020) evaluated the fracture toughness (J integral) of Complex Phase steel, Dual Phase steel, Trip-Aided Bainitic Ferritic steel and Quenching and Partitioning steel, through different methodology. Singh A et. al. (Singh A et. al. 2020) determined CTOD and other fracture parameters using the in plane displacement near the crack tip, which was obtained by a digital image correlation software NCORR.

From the above literature review, it was found that none of the researcher had considered and optimized the response parameters like Notch Tip Opening Displacement (NTOD), Max. Load, Failure Load, and J integral. A Single Edged Notched Tension (SENT) specimen is considered in this work. The reason behind choosing the SENT specimen is because it can be a very good representative of the pipe for both uniaxial and biaxial loading conditions. Within this background, the major aim of the present paper is to evaluate the J integral of thin ductile sheets and to examine the significance of the measured J integral to explain the fracture resistance of AA 5052 sheets. Furthermore, it is also aimed at investigating the effect of specimen and notch parameters on response parameters.

2 RESPONSE SURFACE METHODOLOGY (RSM)

It is a statistical method to find the relationships between several explanatory variables and response variables. In this method an optimal response is obtained from a sequence of designed experiments. The second-degree polynomial can be used to maximize, minimize or attain a target value for the response variables. RSM can also be extended to multi objective optimization, where the optimum values for the response variables obtained will satisfy more than one objective (Sumesh C.S. & Ramesh A., 2018). This paper strongly recommends the use of RSM for multi objective optimization studies. RSM is used in this research work as the optimization tool.

In RSM, the relationship between preferred response and independent input variables can be characterized in the following equation;

$$w = \emptyset(T) \quad (1)$$

Where w is the preferred response and $\emptyset$ is the response surface function. The following equation (2) represents the response surface model;

$$w = \beta_0 + \sum_{n=1}^{k} \beta_n x_n + \sum_{n=1}^{k} \beta_{nn} x_n{}^2 + \sum_{n=1}^{k-1}\sum_{m=1}^{k} \beta_{nm} x_n x_m + \varepsilon \; for\; n < m \quad (2)$$

Where w is the response to predict, β_0, β_n $(n = 1,2,\ldots\ldots,k)$ and $\beta_{nm}(n = 1,2,\ldots\ldots,k,\ m = 1,2,\ldots\ldots,k\,)$ are the unknown regression coefficients. These coefficients can be calculated using method of least squares. Also, ε is the random errors and $x_{1,}x_2 \ldots\ldots\ldots.. x_k$ are input parameters that influence the output response w, k is the number of input variables. Equation (2) can be re-written as;

$$\varepsilon = w - \beta_0 + \sum_{n=1}^{k} \beta_n x_n + \sum_{n=1}^{k} \beta_{nn} x_n{}^2 + \sum_{n=1}^{k-1}\sum_{m=1}^{k} \beta_{nm} x_n x_m \quad for\; n < m \quad (3)$$

In order to minimize the sum of the squares of the errors ε_n, the method of least squares chooses β values accordingly. The least square function is,

$$L = \sum_{n=1}^{k} \varepsilon_n{}^2 \quad (4)$$

Substituting for ε_i from (3) into (4) and differentiate (4) with respect to β, regression coefficients can be obtained.

Table 2 gives the level of input parameters taken for optimization. The range of the values are selected by analyzing the previously published literatures.

Table 2. Levels of the input parameters

	Thickness, T (mm)	Width, W (mm)	Notch Length to Width Ratio, A/W
High	4	30	0.3
Medium	3	25	0.2
Low	2	20	0.1

3 UNIAXIAL TENSILE TEST OF SENT SPECIMENS – EXPERIMENTAL DETAILS

Using Central Composite Design (CCD) in RSM, the 20 combinations of parameters were generated using the Minitab software. For each combination of parameters, SENT specimens are prepared, shown in fig.1, as per ASTM E1820 standards (ASTM code E1820 2001). Each of these specimens are mounted on a UTM and loaded until the specimen fails. From the load – displacement graph, obtained from the tensile test, Max Load and Failure load are noted. A fractured specimen, after load test is shown in fig.2. Using the Profile Projector, the NTOD was measured and is shown in fig.3. Experiments were carried out for all the combinations of specimen and notch parameters and responses are measured. The results are tabulated and shown in Table 3.

Fig. 1: Specimens as per ASTM E1820 standards

Fig. 2: Fractured Specimens at the end of load test

Fig. 3: NTOD Measurement using Profile Projector

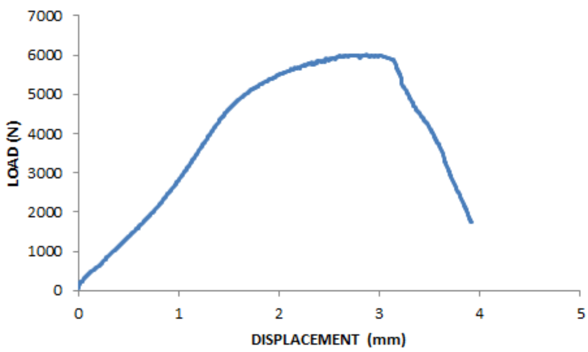


Fig. 4: Load – Displacement graph (For Specimen T = 3mm, W = 25mm, A/W = 0.2)

Table 3. Trails along with corresponding outputs

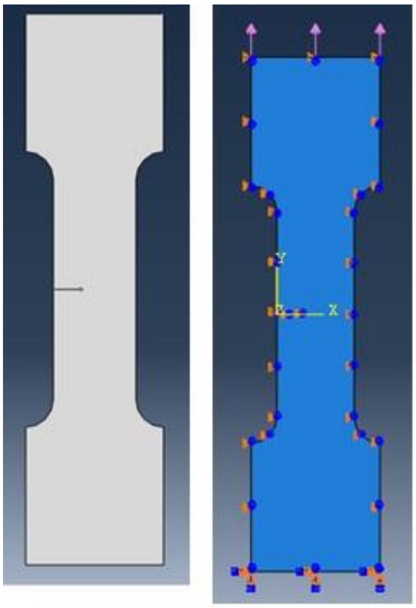
Trails	T (mm)	W (mm)	A/W	NTOD (mm)	Max. Load (N)	Failure Load (N)	J Integral (MPa √m)
1	3	25	0.3	3.07	4705.0	3180.0	0.005942
2	3	25	0.2	2.62	6007.5	5985.0	0.007640
3	3	25	0.2	2.62	6127.5	5962.5	0.007640
4	2	20	0.1	1.04	3108.0	1608.0	0.004680
5	3	25	0.1	1.40	7592.0	7544.0	0.007582
6	3	25	0.2	2.62	6112.5	5467.5	0.007640
7	3	20	0.2	1.79	3644.0	1592.0	0.006870
8	4	25	0.2	2.60	8420.0	8290.0	0.008550
9	3	25	0.2	2.62	6111.0	5962.5	0.007640
10	4	30	0.1	1.22	14250.0	12780.0	0.009920
11	2	30	0.1	1.22	6510.0	6322.5	0.006290
12	4	20	0.3	2.99	3420.0	88.0	0.007870
13	3	30	0.2	3.29	8460.0	8340.0	0.008615
14	4	20	0.1	1.37	6915.0	6862.5	0.008560
15	2	25	0.2	2.07	3992.0	3440.0	0.005060
16	3	25	0.2	2.62	6352.5	5947.5	0.007640
17	2	30	0.3	3.54	4335.0	3875.0	0.004560
18	2	20	0.3	1.67	1770.0	1032.0	0.003860
19	3	25	0.2	2.62	5955.0	5325.0	0.007640
20	4	30	0.3	3.54	9320.0	9040.0	0.008930

4 NUMERICAL CALCULATION OF J INTEGRAL USING FEM

There are several techniques available in the literature to determine fracture toughness of this plates. In this study, a two-dimensional plane stress numerical analysis of the single edge notched tensile (SENT) specimen was done using software package ABAQUS16.3. Figure 5a, shows the part created for the analysis and 5b shows the boundary conditions applied to the part. The bottom edge of the part is encastered and upper edge is allowed to move in the vertical direction only. PLANE 82 element was used for this fracture mechanics analysis. The crack tip was modeled by converting the quadrilateral iso-parametric element in to a special element with mid side nodes moved to the quarter points, called quarter point element. 10 contours were applied at the crack tip, to determine the energy release rate. Figure 6a shows the meshed part and 6b shows the zoomed view of the notch tip. In this numerical analysis, the material non-linearity was accounted for by imputing the experimental stress – strain data of the material presented in the section 3. The numerical model thus developed is validated with the experimental results for NTOD. However, only monotonically increasing loading was considered in this study. The J integral values are obtained from the converged nonlinear analysis. Figure 7 shows the deformed shape of the SENT specimen. Using the validated model, simulations were run for the same 20 combinations shown in Table 3 and J integral values are obtained. The mechanical properties, of the Aluminium alloy AA5052, used in the model are given in the Table 4.

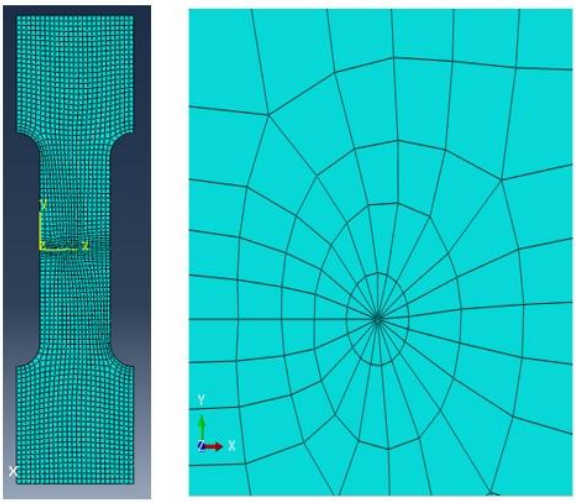
Table 4. Material Properties for AA 5052 (S.Ghosh et. al, 2004)

Density (Kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio
2680	70300	0.33



(a) (b)

Fig. 5: Finite Element Model of SENT Specimen



(a) (b)

Fig. 6: Finite Element Model of SENT Specimen

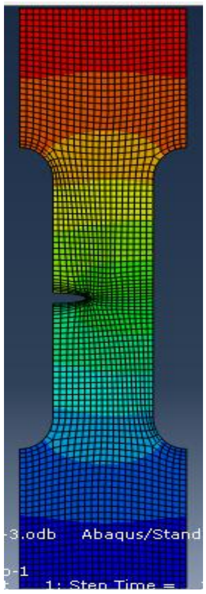


Fig. 7: Deformed Model of SENT Specimen

5 RESULTS AND DISCUSSIONS

A full quadratic Analysis of Variance (ANOVA) was performed on each response separately. In the ANOVA table, all the terms having p value greater than 0.05 were removed (they are considered as insignificant) and once again ANOVA was performed. Using residual plots, it was found that, the values of responses given in Table 5, follows normal distribution. Also, R^2 value from the ANOVA table was checked to validate the model. It was found that R^2 value for all the responses are close to 100%, which indicated that the predicted model can be used for optimization studies. Main effect plots were plotted for all responses, to study the influence of design parameters one at a time. Contour and surface plots are also plotted by considering two parameters at time.

5.1 Analysis of Specimen and Notch Parameters on NTOD

From the ANOVA Table for NTOD, it was observed that, all square terms and interaction terms are insignificant. The R square value was found to be 87.11%. Figure 2 shows the main effect plot for NTOD. From this figure, all parameters have significant influence on NTOD. NTOD increases with increase in specimen thickness.

More the thickness, more the failure load. In this study, NTOD was measured at the end of loading, NTOD will be high due to high failure load. Similarly, for width of the specimen. When width of specimen increases, NTOD also increases, because the failure load is high. But increase in A/W ratio or increase in notch length, decreases the NTOD. This is due to less load is required to failure the specimen having more notch length.

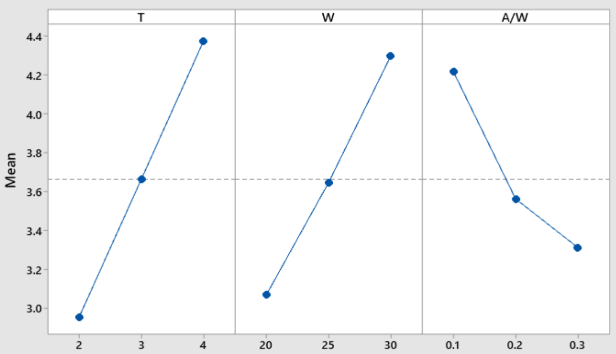


Fig. 2: Main Effects plot for NTOD (mm)

5.2 Analysis of Specimen and Notch Parameters on Max Load

From the ANOVA Table for Max Load, it was observed that, all square terms are insignificant. The R square value was found to be 99.86%. Figure 3 shows the main effect plot for Max Load. From this figure, all parameters have significant influence on Max Load. When the thickness and width of specimen increases, the maximum or ultimate load it can take will also increases. But increase in A/W ratio or increase in notch length, decreases the Max Load. This is because, more the notch length less the ultimate load, it's obvious.

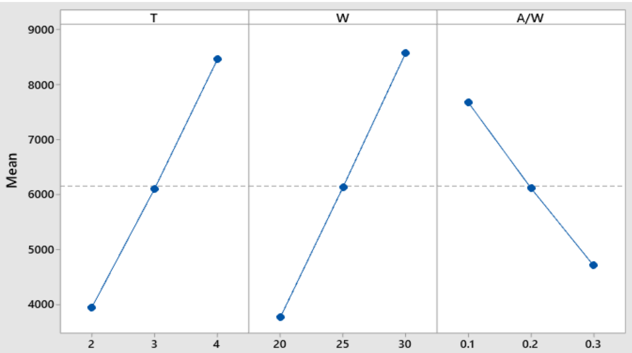


Fig. 3: Main Effects plot for Max. Load (N)

5.3 Analysis of Specimen and Notch Parameters on Failure Load

From the ANOVA Table for Failure Load, it was observed that, all square terms and interaction between width and notch length to width ratio are insignificant. The R square value was found to be 96.25%. Figure 4 shows the main effect plot for Failure load. From this figure, all parameters have significant influence on Failure load. The same justification discussed in the previous section is applicable here as well.

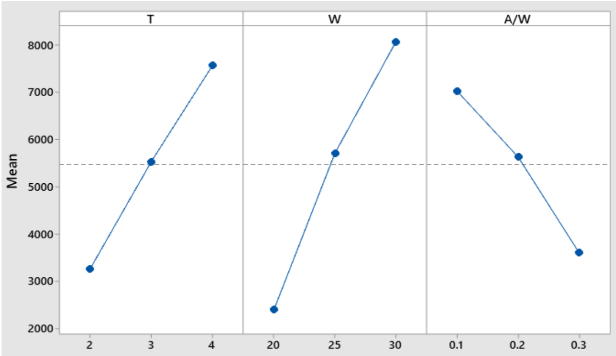


Fig. 4: Main Effects plot for Failure Load (N)

5.4 Analysis of Specimen and Notch Parameters on J Integral

From the ANOVA Table for J integral, it was observed that, all square terms and interaction between width and notch length to width ratio are insignificant. The R square value was found to be 80.06%. Figure 5 shows the main effect plot for J integral. From this figure, specimen thickness has significant influence on J integral. As it is mentioned in section 4, J integral represents amount of energy released per unit fracture surface area. The same justification discussed in the previous section is applicable here as well. When the specimen thickness and width increases, the specimen will take more load. This means resistance to fracture increases, but when fracture occurs the amount of strain energy released will be high. But when the notch length increases, the specimen could take only less load. Hence energy release rate will be in decreasing trend.

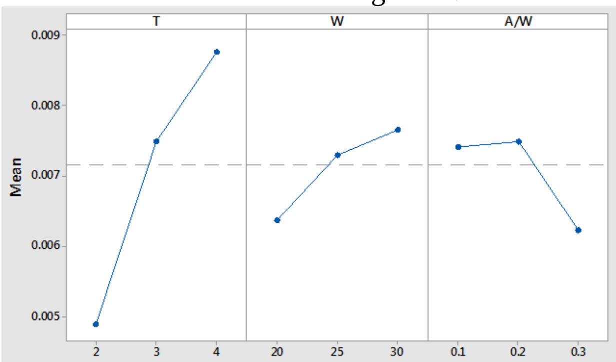


Fig. 5: Main Effects plot for J Integral (MPa√m)

5.5 Multi Objective Optimization of Specimen and Notch Parameters using RSM

Multi objective optimization means determination of an optimal combination of design parameters wherein which all the responses can be achieved simultaneously. The optimization plot is shown in Fig.6. The multi objective optimized values of specimen and notch parameters are shown in the square brackets. The values are Specimen

Thickness = 4 mm, Specimen Width = 30 mm and Ratio of Notch length to Width of specimen = 0.1 mm.

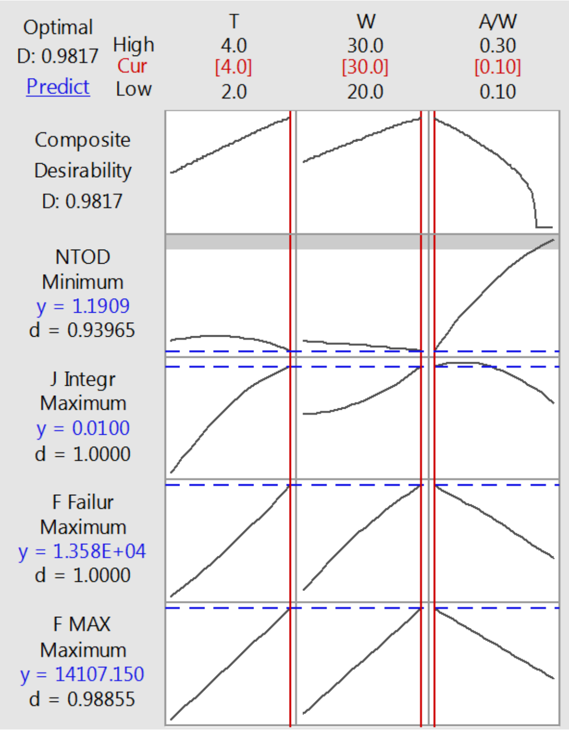


Fig. 6: Optimization Plot

In this plot, y values indicate the predicted values of responses, at the optimal condition. The values against 'd' means the individual desirability of responses and D represents the overall desirability, which is close to one.

Using the optimized values, a simulation was run in the already validated model. The comparison of the results is given in the Table 6. The table shows that the maximum error is less than 10%, which means that the developed numerical model can predict the responses accurately.

6 CONCLUSION

In this work, the influence of specimen and notch parameters on NTOD, Failure Load, Max Load and J integral were studied. ANOVA was performed on each response to obtain the significant parameter. Multi objective optimization was done, to obtain the optimal combination of rolling parameters to achieve the response objectives simultaneously.

Table 6: Comparison of results between RSM and Simulation

Sl No	Output Parameters	From RSM	From Experiment	Percentage Error
1	J Integral (MPa√m)	0.0101	0.0099	1.98
2	NTOD (mm)	1.20	1.24	3.33
3	Failure Load (N)	13580	12780	5.89
4	Max. Load (N)	14150	14250	0.71

The main conclusions obtained from this work are given below;

- From the regression analysis for NTOD, Max. Load, Failure Load and J integral, R^2 was found to be 87.11%, 99.86%, 96.25% and 80.06% respectively. This means the response data are very close to the fitted regression line.
- From the ANOVA results, the specimen thickness was found to be the most significant factor for all the output responses.
- To achieve J integral, Failure Load, Max Load and NTOD, specimen thickness and width should be high and at low notch length to width ratio.
- Multi objective optimization analysis shows that the objectives of all the responses can be achieved simultaneously at specimen thickness = 4 mm, Specimen Width = 30 mm, and Notch length to Width ratio = 0.1.
- The numerical model developed, to optimize the specimen and Notch parameters, can accurately predict all the output responses considered in this work.

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