Optimization of Hollow Specimen Dimensions in Torsion Testing of AISI 1020 Steel using Grey Relational Analysis

Rajkumar.D.Patil[1] Purushottam.N.Gore[2] Prashant A.Naik[3] Uttam S.Bongarde[4]
[1,3,4]Assistant Professor [2]Associate Professor
[1,2,3,4]Department of Mechanical Engineering
[1,2,3,4]D.K.T.E.'s Textile and Engineering Institute, Ichalkaranji, Maharashtra-416115, India

Abstract— This paper investigates the effects and parametric optimization of specimen dimensions for torsion testing of AISI 1020 steel using grey relational analysis. Four dimension parameters viz. outer diameter, inner diameter, useful length, fillet radius are considered and experiments are conducted based on L_9 orthogonal array (OA).Torsion testing responses viz. modulus of rigidity (G), yield shear stress (τ_y), ultimate shear stress (τ_{ut}) of hollow specimen are calculated for every experimental runs. For maximum τ_y and minimum G and $\tau_{ut,}$ specimen dimensions are optimized based on Taguchi method coupled with grey relational analysis. Analysis of variance (ANOVA) is performed to investigate contribution of each specimen dimension on the output parameters and observed that outer diameter is significant specimen dimension that affects the responses. Confirmation test using optimal specimen dimensions shows good agreement to the predicted value.

Key words: Torsion, Modulus of Rigidity, Yield Shear Stress, Ultimate Shear Stress, Taguchi Grey Analysis, ANOVA

I. INTRODUCTION

The strength and rigidity of the material under torsion is found in torsion test .The material is tested in torsion by using proper test procedure. It includes mounting a specimen on the testing machine. The torque is applied incrementally and both the applied torque and the corresponding angle of twist are measured. Torsion formulae, relationships and the measured dimensions, are used to determine shear stress and shear strain. The torque vs. angle of twist, and shear stress vs. shear strain curves are plotted. From which material shear properties can be determined [1]. An experimental study of fracture in different types of stress state is made to construct failure criterion. Shear tests as well as combined biaxial tests with thin-walled tubular specimens of different geometry are conducted [2]. Zarroug et al. [3] investigates effect of combined tension–torsion loading on the Mild steel (En8) specimen. The finite element analysis (FEA) results are validated against experimental results. Graber et al. [4] used new approximate method for plotting stress-stain curves from torsion test results. The best accuracy is obtained by using thin walled tubular specimens. It uses the concept of the "effective" length during deformation for short specimens.

Pavel et al. [5] performed torsion test experiments on solid thick walled cylindrical specimens for the failure criterion construction. Berto et al. [6] conducted 70 torsion tests at room temperature on notched specimens made of polymethyl-methacrylate. Semi-circular notches as well as U- and V notches (with an opening angle equal to 120°) are made, with a root radius ranging from 0.1 to 7.0 mm. The notch root radius and the notch depth is varied to plot torque vs. angle of twist curve. Han-Chin Wu et al. [7] conducted series of experiments on cast and extruded high purity aluminium material under monotonic large strain torsion condition. Tubular specimens of different gage lengths (long, medium and short) are used to study both free end and fixed end torsions. The torque versus angle of twist curves was plotted. The true shear stress–strain curves are drawn by using the modified Nadia method. The effect of specimen geometry is studied. For torsion in large strain range, long, thick walled tubular specimen is used. Bressan et al. [8] developed a computerized prototype machine. This torsion machine was consists of an electric motor, a wheel, a horizontal shaft and a control and acquisition data system. A torsion angle and the torque were measured by encoder and load cell. Torsion experiment is conducted at constant angular speed. The annealed materials such as 1020 steel, brass, and pure copper and pure aluminium were used. The strain rate sensitivity parameter m-values were 0.072 and 0.045 for steel and brass during torsion.

II. DESIGN OF EXPERIMENT (DOE)

The experiment was performed according to design of experiment as the design of experiment saves time and cost, reducing number of experiments. The output parameters viz. modulus of rigidity (G), yield shear stress (τ_y), ultimate shear stress (τ_{ut}) are selected. Specimen dimensions affect the torsion test results. So in order to find dimension levels, studied different papers on torsion testing and discuss with industry experts. From the literature review 80 % geometric progression is used for selecting the levels of Taguchi design. Hollow specimen dimensions of mild steel (AISI 1020) viz. outer diameter, inner diameter, useful length, fillet Radius are selected for research. The specimen dimensions and their levels selected for the present investigation are shown in table 1.

Sr. No.	Specimen Dimensions	Level I	Level II	Level III
1.	Outer diameter	12.0	10.0	8
2.	Inner diameter	6.0	4.8	3.8
3.	Useful length	25.0	20.0	16.0
4.	Fillet radius	3.0	2.5	2.0

Table 1: Selected specimen dimensions and their levels

Mechanical and chemical properties of AISI 1020 steel are shown in table 2 and table 3 respectively.

Sr. No.	Property	Value	Units
1	Maximum stress	400-560	N/mm^2
2	Yield Stress	300-440 min.	N/mm^2
3	0.2 % proof stress	280-420 min.	N/mm^2

4	Poisson's ratio	0.29	N/A
5	Shear modulus in XY	77000	N/mm^2
6	Mass density	7900	Kg/m^3

Table 2: Mechanical properties of mild steel (AISI 1020) [11]

Element	Carbon	Si	Mn	S	P
(%)	0.15-0.25	0.35 max	0.3-0.9	0.05 max	0.05 max

Table 3: Chemical composition of mild steel (AISI 1020) [11]

A. *Selection of Orthogonal Array*

In Taguchi method, an orthogonal array is employed to reduce the number of experiments for finding optimal specimen dimensions. The selection of OA depends on the total degrees of freedom (DOF) required to investigate main and interaction effects.

The orthogonal array is selected according to the number of levels of various factors. In this study, to conduct the experiments 4 factors with 3 levels each were selected. Degree of Freedom (DOF) was calculated from Eq. (1) as,

$$(DOF)\ R = P\ (L - 1) \quad (1)$$

(DOF) R = Degrees of freedom
P = Number of parameters
L = Number of levels
(DOF) R = 4(3 – 1) = 8

Total DOF of the orthogonal array (OA) should be greater than or equal to the total DOF required for the experiment. Thus, L_9 orthogonal array was selected to make the further experiments. This array specifies 9 experiments. The experiments were conducted according to the trial condition using L 9 orthogonal array. A total 27 experiments are required to perform to find out effect of process parameters on performance measures. The L9 array is shown in table 4.

Expt No.	Independent Variables			
	Variable 1	Variable 2	Variable 3	Variable 4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 4: L_9 Orthogonal Array [9]

As per the L_9 orthogonal array specimen dimensions with their levels are shown in table 5.

Parameters Expt. No	Outer diameter mm	Inner diameter mm	Useful length mm	Fillet radius mm
1	12.0	6.0	25.0	3.0
2	12.0	4.8	20.0	2.4
3	12.0	3.8	16.0	2.0
4	10.0	6.0	20.0	2.0
5	10.0	4.8	16.0	3.0
6	10.0	3.8	25.0	2.5
7	8.0	6.0	16.0	2.5
8	8.0	4.8	25.0	2.0
9	8.0	3.8	20.0	3.0

Table 5: Design of experiment

III. RESULTS AND DISCUSSION

The torsion test results for modulus of rigidity, yield shear stress and ultimate shear stress are included in table 6. Fig. 1 and fig. 2 shows hollow specimens before and after the torsion testing on digital torsion testing machine having capacity 200 Nm. Modulus of rigidity, yield shear stress and ultimate shear stress are optimized in this study and this is a multi-response optimization problem. For multi-response optimization, grey relational analysis coupled with Taguchi method is used in this study [10].

Fig. 1: Mild steel hollow specimens

Fig. 2: Mild steel hollow specimens after failure

A. *Grey Relational Analysis*

In order to optimize the, outer diameter, inner diameter useful length, and fillet radius simultaneously, grey relational analysis (GRA) has been utilized. For multi response optimization using GRA, following steps were used in order to obtain grey relational grade (GRG). [10]

Conversion of experimental data into S/N ratios

The S/N ratios for three output measures are shown in table 6.

Expt. No.	G GPa	τ_y MPa	τ_{ut} MPa	S/N ratio		
				G	τ_y	τ_{ut}
1	78.40	349.28	433.63	-37.88	50.86	-52.74
2	77.58	353.31	434.23	-37.79	50.96	-52.75
3	77.64	357.24	435.47	-37.80	51.05	-52.77
4	79.17	346.64	459.35	-37.97	50.79	-53.24
5	81.03	356.84	445.21	-38.17	51.04	-52.97
6	77.78	344.43	432.19	-37.81	50.74	-52.71
7	79.32	330.92	346.41	-37.98	50.39	-50.79
8	77.50	352.01	413.28	-37.78	50.93	-52.32
9	77.78	352.87	417.61	-37.81	50.95	-52.41

Table 6: Experimental results for responses and Sequence of S/N ratio

B. *Normalization of S/N Ratio*

Data pre-processing is the first step in GRA. It involves transforming an original sequence into a comparable sequence. A series of various units must be transformed to dimensionless quantities. Experimental results are thus normalized in a range of 0–1.For normalization of G and τ_{ut} data, smaller the better criterion (Eq. 2) and for τ_y data larger the better criterion (Eq. 3) are used. The processed data after normalization of S/N ratio is given in table 7.

$$x_i^*(k) = \frac{max\, x_i^0(k) - x_i^0(k)}{max x_i^0(k) - min x_i^0(k)} \quad (2)$$

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{max\, x_i^0(k) - min x_i^0(k)} \quad (3)$$

Expt. No.	Modulus of rigidity	Yield shear stress	Ultimate shear stress
Ref. sequence	1.0000	1.0000	1.0000
Comparability sequence			
1	0.2592	0.7056	0.7958
2	0.0233	0.8554	0.8007
3	0.0406	1.0000	0.8108
4	0.4787	0.6064	1.0000
5	1.0000	0.9854	0.8892
6	0.0812	0.5228	0.7840
7	0.5213	0.0000	0.0000
8	0.0000	0.8073	0.6255
9	0.0812	0.8392	0.6624

Table 7: Sequence after data pre-processing

C. Determination of Deviation Sequence

The deviation sequence $\Delta_{oi}(k)$ is the absolute difference between the reference sequence $x_i^0(k)$ and the comparability sequence $x_i^*(k)$ after normalization.It is determined using Eq. (4), deviation sequences are displayed in table 8.

$$\Delta_{oi}(k) = |x_0^*(k) - x_i^*(k)| \quad (4)$$

Deviation sequence	$\Delta_{01}(01)$	$\Delta_{01}(02)$	$\Delta_{01}(03)$
No.1, i=1	0.7408	0.2944	0.2042
No.2, i=2	0.9767	0.1446	0.1993
No.3, i=3	0.9594	0.0000	0.1892
No.4, i=4	0.5213	0.3936	0.0000
No.5, i=5	0.0000	0.0146	0.1108
No.6, i=6	0.9188	0.4772	0.2160
No.7, i=7	0.4787	1.0000	1.0000
No.8, i=8	1.0000	0.1927	0.3745
No.9, i=9	0.9188	0.1608	0.3376

Table 8: The deviation sequences

D. Calculation of Grey Relational Coefficient (GRC)

GRC for all the sequences expresses the relationship between the ideal (best) and actual normalized S/N ratio. If the two sequences agree at all points and then their Grey relational coefficient is 1. The Grey relational coefficient can be calculated by Eq. (5).

$$\gamma(x_0(k), x_i(k)) = \frac{\Delta_{min} + \zeta.\Delta_{max}}{\Delta_{0i}\ (k) + \zeta.\Delta_{max}} \quad (5)$$

Where,

$\Delta_{min} = min.min\ \Delta_{0,i}\ (k)$

$\Delta_{max} = max.max\ \Delta_{0,i}\ (k)$

$\Delta_{0i}\ (k)$Is the deviation sequence and

ζ = distinguishing coefficient, $\zeta \in (0,1)$ and for present study, ζ is set as 0.5.

From the data presented in Table 8 of deviation sequence, Min. and Max. Values ($\Delta_{max}(k)$ and $\Delta_{min}(k)$) are as follows:

$\Delta_{max} = \Delta o_8\ (1) = \Delta o_7\ (2) = \Delta o_7\ (3) = 1.0000,$

$\Delta_{min} = \Delta o_5\ (1) = \Delta o_3\ (2) = \Delta o_4\ (3) = 0.0000$

E. Determination of Grey Relational Grade (GRG)

The overall evaluation of the multiple performance characteristics is based on the Grey relational grade. The Grey relational grade is an average sum of the Grey relational coefficients, which can be calculated using Eq. (6).

$$\gamma(x_0, x_i) = \frac{1}{m}\sum_{i=1}^{m} \gamma(x_0(k), x_i(k)) \quad (6)$$

Where,

$\gamma(x_0, x_i)$ = Grey relational grade for the j_{th} experiment and m is the number of performance characteristics. Grey relational coefficients and GRG are given in the table 9.

Seq.	Modulus of rigidity	Yield shear stress	Ultimate shear stress	Grade Value	Rank
1	0.4030	0.6294	0.7100	0.5808	5
2	0.3386	0.7757	0.7150	0.6098	4
3	0.3426	1.0000	0.7255	0.6894	2
4	0.4896	0.5596	1.0000	0.6830	3
5	1.0000	0.9716	0.8186	0.9301	1
6	0.3524	0.5117	0.6983	0.5208	8
7	0.5109	0.3333	0.3333	0.3925	9
8	0.3333	0.7218	0.5717	0.5423	7
9	0.3524	0.7566	0.5969	0.5687	6

Table 9: Grey relational coefficients and GRG values

F. Analysis of Grey Relational Grade and Selection of Optimal Level of Parameters

It is clearly observed from Table 9, the specimen dimension “setting of experiment no.5” has the highest Grey relational grade (0.9301) thus the 5th number experiment gives the best multiple performance characteristics among the 9 experiments. Using Taguchi method, response table has been generated to find out the effect of each level of specimen dimensions on Grey relational grade as shown in Table 10. Basically, larger the Grey relational grade, better the corresponding output measures. From the response table 11 for Grey relational grade, the best combination of the process parameters is set with A2B2C3D1.

Parameter	DOF	Seq. SS	Adj.SS	Adj.MS	% Contri.
OD diameter	2	0.067	0.067	0.033	38.01
ID	2	0.032	0.032	0.016	18.16
LU	2	0.022	0.022	0.011	12.94
R	2	0.054	0.054	0.027	30.87
Total	8	0.176	-	-	100

Table 10: ANOVA for Grey Relational Grade

Levels	OD	ID	LU	R
1	0.626	0.552	0.548	0.693
2	0.711	0.694	0.620	0.507
3	0.501	0.592	0.670	0.638
Max-Min	0.21	0.14	0.12	0.18
Ranking	1	3	4	2
Total mean value of GRG is 0.6130				

Table 11: Response Table for Grey Relational Grade (GRG)

G. Prediction of Grey Relational Grade under optimum Parameters

The optimal Grey relational grade η_{opt} is predicted using Eq. (7),

$$\eta_{opt} = \overline{T} + (\overline{A}_2 - \overline{T}) + (\overline{B}_2 - \overline{T}) + (\overline{C}_3 - \overline{T})\ (\overline{D}_1 - \overline{T})\ 7)$$

$\eta_{opt} = 0.9301$

Where

$\overline{T}$ = Total mean of GRG

$\overline{A}_2, \overline{B}_{3,} \overline{C}_1, \overline{D}_2$= average values of response at the respective levels of parameters A, B, C and D respectively.

H. Confirmation Test

Finally, three confirmation experiments were conducted using the optimal process parameters (A3, B2, C3 and D1). The measured mean value at optimal parameters for outer diameter, inner diameter, useful length and fillet radius is 10 mm, 4.8 mm, 16 mm and 3 mm respectively. The grey relational grade computed is 0.9301. Table 12 shows comparison of estimated grey relational grade with the actual grey relational grade obtained in the experiment using optimal specimen dimensions.

Sr. No	Process Parameters	Initial setting	Predicted Value	Experimental value
1	Optimal parameter	A2B2C3 D1	A2B2C3D 1	A2B2C3 D1
2	Modulus of rigidity (GPa)	81.03		81.03
3	Yield shear stress (MPa)	356.84		356.84
4	Ultimate shear stress (MPa)	445.21		445.21
6	Grey Relational Grade	0.93	0.93	0.93

Table 12: Results of confirmation test

IV. CONCLUSIONS

This paper presents the optimization and the effect of specimen dimensions on modulus of rigidity, yield shear stress and ultimate shear stress in torsion testing of mild steel (AISI 1020) using Taguchi OA with grey relational analysis. Optimal combination of specimen dimensions is obtained as A2, B2, C3, and D1. The measured mean value at optimal parameters for outer diameter, inner diameter, useful length and fillet radius is 10 mm, 4.8 mm, 16 mm and 3 mm respectively. Based on ANOVA, the most significant parameter is outer diameter. The validity of analysis is checked by a confirmation test.

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