Effect of Specimen Dimensions on Yield Shear Stress in Torsion Testing of AISI 1020 Steel by using Taguchi with GRA

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Abstract— This current research work aims at studying the influence of solid specimen dimensions such as total length, useful length, outer diameter and fillet radius on yield shear stress of mild steel (AISI 1020) in torsion testing. L9 orthogonal array was selected for design of experiments. Three output parameters of torsion testing such as modulus of rigidity, yield shear stress and ultimate shear stress were calculated by using Nadai method. Single objective optimization was done by using Taguchi method. Further effort was made to simultaneously optimize the specimen dimensions using grey relational analysis (GRA). It was found that, yield shear stress was minimum for the specimen dimensions with total length 130 mm, useful length 50 mm, outer diameter 8 mm and fillet radius 3 mm. The confirmation test was also carried out to check the GRA results.

Key words: Torsion Testing, Grey Relational Analysis; Yield Shear Stress; Taguchi Method; Nadai Method, smaller-the-better

I. INTRODUCTION

Torsion experiment is performed to determine different mechanical properties in new product design and development. The problems listed related to torsion tests as: material homogeneity, specimen geometry, strain measurement and determination of shear stress-strain curve [1].The results were obtained in combined tension–torsion loading tests for Mild steel (En8) specimen. The specimens were tested in two different ways: (i) upholding tensile force or axial displacement constant and increasing torque or angle of twist (ii) keeping torque or angle of twist constant and increasing load or axial displacement. In this study, (i) method was used to conduct torsion experiment [2].The torsion machine was established using encoder and load cell for measurement of angle and torque [3].Nadia method was used for calculation of shear stress and shear strain in torsion test results [4]. In this study, torsion tests are performed on solid specimens of AISI 1020 steel using digital torsion testing machine having capacity 200 Nm.

Taguchi method is a powerful tool for design of experiments (DOE) which is used for single objective optimization. It is an important tool to recognize critical parameters and also forecast optimal settings of each process parameter. Taguchi parameter technique is a single parameter optimization based on signal to noise ratio [12]. Taguchi methodology

GRA converts m y has been widely embraced in the experimental design related to a large variety of machining processes [5-10]. ulti-objective optimization problem in a single objective optimization problem. Grey relational grade (GRG) technique was used to optimize machining parameters during turning. Analysis of variance (ANOVA) is performed to find most significant parameter [11].

II. DESIGN OF EXPERIMENTS

Taguchi technique has used to plan the experiments. Orthogonal arrays were designed in 1940's and used in designing experiments. It has used to reduce the number of experiments conducted during full factorial experiments. Based on strength of specimens and ASTM A938-07, the specimen dimensions and their levels are given in table 1.

Sr. no.	Specimen dimensions	Level I	Level II	Level III
1.	Total length	203.0	162.0	130.0
2.	Useful length	78.0	62.4	50.0
3.	Outer diameter	10.0	8.0	6.0
4.	Fillet radius	3.0	2.5	2.0

Table 1: Selected Specimen Dimensions and their Levels for Solid 1020 Steel

The control factors are 4 and levels are 3, hence the Degree of freedom are 4(3-1) = 8. The no of experiments in the OA should be equal to or greater than Degrees of freedom, so L9 OA has been selected. The required combination of input parameters using L9 orthogonal array are listed in table 2.

Parameters → / Expt. No ↓	Total length mm	Useful length mm	Outer diameter Mm	Fillet radius mm
1	203.0	78.0	10.0	3.0
2	203.0	62.4	8.0	2.5
3	203.0	50.0	6.0	2.0
4	162.0	78.0	8.0	2.0
5	162.0	62.4	6.0	3.0
6	162.0	50.0	10.0	2.5
7	130.0	78.0	6.0	2.5
8	130.0	62.4	10.0	2.0
9	130.0	50.0	8.0	3.0

Table 2: Taguchi L9 Standard Orthogonal Array Design Matrix for Solid 1020 Steel

The mild steel solid specimens as per table 2 were prepared. The specimens as per L9 orthogonal array are shown in figure 1.The torsion test has been performed on digital torsion testing machine of capacity 200 Nm. Each experiment has conducted for three trials. The specimens have been tested till failure as shown in fig.2.

Fig. 1:.Mild Steel Solid Specimen

Fig. 2: Specimens after Torsion

III. TAGUCHI'S OPTIMIZATION METHOD

The yield shear stress value and S/N ratio against each trial are shown in table 3.

Exp. No.	Yield shear stress (MPa)				S/N ratio (SB)	Mean
	1	2	3	Avg.		
1	380.00	381.00	382.50	380.00	-51.595	380.00
2	378.00	379.00	380.00	379.00	-51.572	379.00
3	398.00	397.00	399.00	399.00	-52.019	399.00
4	385.00	383.00	386.00	385.00	-51.709	385.00
5	388.87	389.87	387.87	387.87	-51.773	387.87
6	392.00	391.00	390.00	390.00	-51.821	390.00
7	385.00	386.00	387.00	386.00	-51.731	386.00
8	392.55	391.05	390.55	390.55	-51.833	390.55
9	372.46	370.60	371.70	370.56	-51.377	370.56

Table 3: Yield Shear Stress Value for each Trial and S/N Ratio against Trial Numbers

From the table 3, yield shear stress has found minimum for the specimen dimensions with total length 130 mm, useful length 50 mm, outer diameter 8 mm and fillet radius 3 mm. The graph showing the effects of specimen dimensions on yield shear stress are shown in Figure 3.

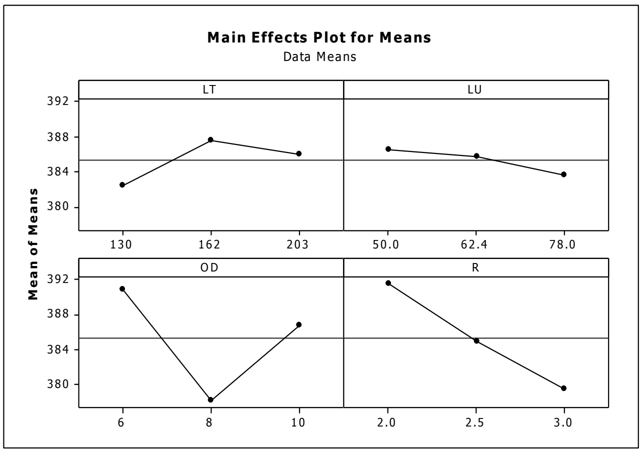

Fig. 3: Effects of Specimen Dimensions on Yield Shear Stress

After analyzing the graphs in Figure 3, it is observed that the yield shear stress decreases with increase in outer diameter and further increases. Also Yield shear stress decreases with increase in useful length.

IV. GREY ANALYSIS FOR 1020 STEEL SOLID SPECIMEN

Expt. No.	Modulus of rigidity	Yield shear stress	Ultimate shear stress
1	-37.779	-51.596	-53.873
2	-37.730	-51.573	-54.036
3	-37.903	-52.020	-54.181
4	-37.842	-51.709	-54.145
5	-37.797	-51.774	-53.529
6	-37.982	-51.821	-54.609
7	-37.856	-51.732	-53.908
8	-37.756	-51.834	-53.968
9	-37.993	-51.377	-53.979

Table 4: Sequence of S/N Ratio

The S/N ratios for each trial numbers and for three output measures are shown in table 4.

A. 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. Usually, each series is normalized by dividing the data in the original series by their average.

Let the original reference sequence and sequence for comparison be represented as xo(k) and xi(k), i=1, 2, . . ., m; k =1, 2, . . ., n, respectively, where m is the total number of experiment to be considered and n is the total number of observation data. Data pre-processing converts the original sequence to a comparable sequence

The "Larger-the-better" is a characteristic of the original sequence and it is used to compare levels in the GRA. As already noted, for these quality characteristics, original sequence should be normalized using Eq.5.11which is reproduced below,

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

The "smaller-the-better" is a characteristic of the original sequence and it is used to compare levels in the GRA. In this experiment, response such as modulus of rigidity, yield shear stress and ultimate shear stress is normalized using "Smaller the better" characteristics. As already noted, for these quality characteristics, original sequence should be normalized using Equation as below,

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

For Experiment No.1, modulus of rigidity value can be normalized as:

$$x_i^*(k) = \frac{(-37.729)-(-37.779)}{(-37.729)-(-37.993)} = 0.188$$

Similar procedure is followed for all performance characteristics and original sequences was normalized which are displayed in Table 5.

Expt. No.	Modulus of	Yield shear	Ultimate
Ref.	1.0000	1.0000	1.0000
Comparability sequence			
1	0.188	0.3402	0.3191
2	0.000	0.3045	0.4698
3	0.658	1.0000	0.6043
4	0.426	0.5169	0.5706
5	0.256	0.6173	0.0000
6	0.959	0.6914	1.0000
7	0.481	0.5519	0.3516
8	0.098	0.7104	0.4067
9	1.000	0.0000	0.4167

Table 5: Sequence after Data Pre-Processing

B. 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.4.13which is rewritten below for easy reference,

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

For experiment no.1, deviation sequence Δ_o1 can be calculated as follows

$$\Delta_{oi}(1) = |1.0000 - 0.188| = 0.812$$
$$\Delta_{oi}(2) = |1.0000 - 0.3402| = 0.6598$$
$$\Delta_{oi}(3) = |1.0000 - 0.3191| = 0.6809$$

Similar procedure is followed for all 9 experiments and Deviation sequence were calculated and displayed in Table 6.

Deviation sequence	$\Delta_{01}(01)$	$\Delta_{01}(02)$	$\Delta_{01}(03)$
No.1, *i=1*	0.812	0.6598	0.6809
No.2, *i=2*	1.000	0.6955	0.5302
No.3, *i=3*	0.342	0.0000	0.3957
No.4, *i=4*	0.574	0.4831	0.4294
No.5, *i=5*	0.744	0.3827	1.0000
No.6, *i=6*	0.041	0.3086	0.0000
No.7, *i=7*	0.519	0.4481	0.6484
No.8, *i=8*	0.902	0.2896	0.5933
No.9, *i=9*	0.000	1.0000	0.5833

Table 6: The Deviation Sequences

C. 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 expressed by Equation as follows:

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

Where, k

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

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

$\Delta_{0i}\ (k)$ Is the deviation sequence and $\zeta =$ distinguishing coefficient, $\zeta \in (0,1)$ And for present study, ζ is set as 0.5.

Investigating the data presented in Table of deviation sequence (Table: 6), we can observe Min. and Max.

Values (Δ_{max} (k) and $\Delta(k)$) as follows:

$\Delta_{max} = \Delta o_1\ (1) = \Delta o_6\ (2) = \Delta o_1\ (3) = \Delta_{07}\ (4)$ =1.0000,

$\Delta_{min} = \Delta o_7\ (1) = \Delta o_3\ (2) = \Delta o_7\ (3) = \Delta o_1\ (4) = 0.0000$

Using Table 6.39 and Eq.5.14 the Grey relational coefficient $\gamma(x_0^*(1).x_0^1(1))$ can be calculated as follows and subsequent values for all experiments are displayed in Table 6.40.

$$\gamma(x_0^*(1).x_0^1(1)) = \frac{0.0000 + 0.5 \times 1.0000}{0.812 + 0.5 \times 1.0000} = 0.3811$$
$$\gamma(x_0^*(2).x_0^1(2)) = \frac{0.0000 + 0.5 \times 1.0000}{0.6598 + 0.5 \times 1.0000} = 0.4311$$
$$\gamma(x_0^*(3).x_0^1(3)) = \frac{0.0000 + 0.5 \times 1.0000}{0.6809 + 0.5 \times 1.0000} = 0.4234$$

D. 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 Equation, represented as:

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

Where, $\gamma(x_O, x_{i)}$= Grey relational grade for the j_{th} experiment and m isthe number of performance characteristics.

Grey relational grade (GRG) for experiment no 1 is calculated as:

$$\gamma(x_0, x_i) = \frac{0.3811 + 0.4311 + 0.4234}{3} = 0.4119$$

Similar procedure is applied for i=1-9. Table 6 shows the Grey relational coefficient for all 9 comparability sequences, grade values and Corresponding rank of each experiment.

No. (Comparability sequence)	Modulus of rigidity	Yield shear stress	Ultimate shear stress	Grade Value	Rank
1	0.3811	0.4311	0.4234	0.4119	9
2	0.3333	0.4182	0.4853	0.4123	8
3	0.5935	1.0000	0.5582	0.7172	2
4	0.4654	0.5086	0.5380	0.5040	4

5	0.4020	0.5665	0.3333	0.4339	7
6	0.9234	0.6184	1.0000	0.8473	1
7	0.4905	0.5274	0.4354	0.4844	6
8	0.3567	0.6332	0.4573	0.4824	5
9	1.0002	0.3333	0.4616	0.5984	3

Table 7: Grey Relational Coefficients and Grade Values

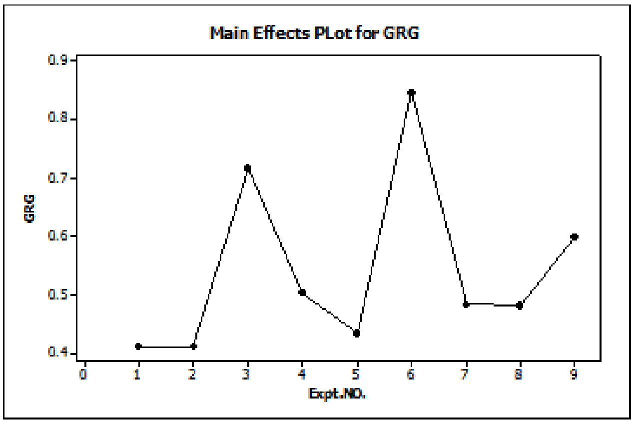

Fig. 4: Graph Showing Experiment No. Versus Respective Grade

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

Analysis of variance (ANOVA) of Grade values has been performed using statistical software, MINITAB on Grey relational grade values to evaluate the influence of specimen dimensions on output parameters. ANOVA for grade values in table 8 shows that all four parameters total length (A), useful length (B), outer diameter (C) and fillet radius (D) significantly affect the output parameters of torsion test under 95% confidence levels. It is clearly observed from Table 7 and Figure 4, the specimen dimension "setting of experiment no.6" has the highest Grey relational grade (0.8473) thus the 6th number experiment gives the best multiple performance characteristics among the 9 experiments. Using Taguchi method, response table has been generated to separate out the effect of each level of specimen dimensions on Grey relational grade as shown in Table 9. Basically, larger the Grey relational grade, better the corresponding output measures. From the response table for Grey relational grade, the best combination of the process parameters is set with A2B3C1D2.

Parameter	DOF	Seq. SS	Adj. SS	Adj. mean SS	% Contribution (P)
LT	2	0.0120	0.0120	0.0060	6.66
LU	2	0.1424	0.1424	0.0712	78.82
OD	2	0.0085	0.0085	0.0042	4.75
R	2	0.0176	0.0176	0.0088	9.76
Total	8	0.1807	-	-	100

Table 8: ANOVA for Grey Relational Grade

Levels	LT	LU	OD	R
1	0.5138	0.4668	0.5805	0.4814
2	0.5951	0.4429	0.5049	0.5813
3	0.5217	0.7210	0.5452	0.5679
Max-Min	0.0813	0.2781	0.0756	0.0999
Ranking	3	1	4	2
Total mean value of GRG is 0.5435				

Table 9: Response Table for Grey Relational Grade (GRG)

F. Prediction of Grey Relational Grade under optimum Parameters

After evaluating the optimal parameter settings, the next step is to predict and verify the improvement of quality characteristics using the optimal parametric combination.

The optimal Grey relational grade η_opt is predicted using equation as below:

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

Where

$\overline{T}$ = overall mean of the response

$\overline{A}_2, \overline{B}_3, \overline{C}_1, \overline{D}_2 =$ average values of response at the respective levels of parameters A, B, C and D respectively.

$$\eta_{opt} = 0.5435 + (0.5951 - 0.5435) + (0.7210 - 0.5435) + (0.5805 - 0.5435) + (0.5813 - 0.5435)$$

$$\eta_{opt} = 0.8473$$

V. CONCLUSIONS

1) It is observed that the yield shear stress decreases with increase in outer diameter and further increases.
2) The yield shear stress has found minimum for the specimen dimensions with total length 130 mm, useful length 50 mm, outer diameter 8 mm and fillet radius 3 mm.
3) It is observed that the yield shear stress decreases with increase in useful length of the specimen.
4) Three confirmation experiments were conducted using the optimal specimen dimensions (A2, B3, C1 and D2). The measured mean value at optimal dimensions for total length, useful length, outer diameter and fillet radius is 162 mm, 50 mm, 10 mm and 2.5 mm respectively. The grey relational grade computed is 0.8473. Table 10, analyses the predicted and experimental results.

Srno	Process Parameters	Initial setting	Predicted Value	Experimental value
1	Optimal parameter	A2B3C1D2	A2B3C1D2	A2B3 C1D2
2	Modulus of rigidity	79.27		79.27
3	Yield shear stress	390.00		390.00
4	Ultimate shear stress	537.57		537.57
6	Grey Relational Grade	0.8473	0.8473	0.8473

Table 10: Predicted and Experimental Values

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