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Effect of Specimen Dimensions on Investigation of Modulus of Rigidity in Torsion Testing

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Abstract - In **the present paper, the effect of different specimen dimensions on the modulus of rigidity of mild steel (AISI 1020) in torsion testing is investigated. The experiments were conducted with dimension variables such as total length, useful length, outer diameter and fillet radius at different levels. For every combination of dimension variables, modulus of rigidity was found. To obtain optimum value of modulus of rigidity, the experimental data was used and effect of varying levels of each variables on the modulus of rigidity was investigated. The Taguchi parameter design and optimization approach is used. Percentage contribution of each dimension variable to decide modulus of rigidity is also calculated by ANOVA approach.**
Keywords**: Modulus of rigidity, total length, useful length, outer diameter, fillet radius**

I.INTRODUCTION

Mechanical testing plays an important role in finding fundamental properties of engineering materials. These can be used in development of new materials. For a material to be used in engineering structure subjected to a load, it is important to know the strength and rigidity of the material to withstand the loads [1]. As a result, numbers of experimental techniques have developed by engineers for mechanical testing of engineering materials. These materials may be subjected to tension, compression, bending or torsion loading. To test the material in torsion the proper test procedure is needed. It involves 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. Using the appropriate formulae, relationships and the measured dimensions, shear stress and shear strain can be determined. Then, plot the torque vs. angle of twist, and shear stress vs. shear straincurve. From which material shear properties can be determined [2].

II.EXPERIMENTAL WORK

Low-carbon steels or mild steel contain up to 0.30 % C. The largest category of this class of steel is flat- rolled products, usually in the cold rolled and annealed condition. The carbon content of these high-formability steels is very low, less than 0.10 % C with up to 0.4 % Mn. Typical uses are in automobile body panels, tin plate and wire products. For rolled steel structural plates and sections, the carbon content may be increased to approximately 0.30 %, with higher manganese content up to 1.5 %[1, 2].

TABLE I CHEMICAL COMPOSITION OF MILD STEEL (AISI 1020)

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

The following specimen dimension variables were selected to study their effects on the modulus of rigidity of AISI 1020 steel in torsion testing.

1. Total length,
2. Useful length,
3. Outer diameter,
4. Fillet radius.

TABLE II PHYSICAL AND MECHANICAL PROPERTIES OF AISI 1020

Sl. No.	Property	Value
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	Elongation	10-14 % min. N/mm^2
5	Shear modulus in XY	77000N/mm^2
6	Mass density	7900 kg/m^3

In order to find dimension variables we have studied different papers on torsion testing and discussion with industry experts. We found that total length, useful length, outer diameter, fillet radius effects on modulus of rigidity of mild steel. 80 % geometric progression is used for selecting the levels of Taguchi design [3, 4, 5].

TABLE III SPECIMEN DIMENSION VARIABLES AND THEIR DIFFERENT LEVELS

Sl. no.	Specimen dimensions	Level I	Level II	Level III
1	Total length	203	162	130
2	Useful length	78	62.4	50
3	Outer diameter	10	8	6
4	Fillet radius	3	2.5	2

Taguchi recommends Orthogonal Array (OA) for design of experiments. OA's are generalized Greco-Latin squares. The design of experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns. The selection of a particular orthogonal array is based on the number of levels of various factors. Here, to conduct the experiments 4 factors with each having 3 levels were selected. Now the Degree of Freedom (DOF) can be calculated by the formula as:

$(DOF) = P*(L - 1)$ -- (1)

$= 4(3 - 1) = 8$

Where (DOF) -Degrees of freedom, P-Number of factors and L-Number of level

However, total DOF of the orthogonal array (OA) should be greater than or equal to the total DOF required for the experiment.Thus, L9 orthogonal array was selected to make the further experiments [9]. This array specifies 9 experiments. The L9 OA comprising of 4 parameters with each having 3 levels are shown in the Table IV.

TABLE IV TAGUCHI L9 STANDARD ORTHOGONAL ARRAY DESIGN MATRIX

Expt. No.	Total length	Useful length	Outer diameter	Fillet radius
1	203	78.0	10	3.0
2	203	62.4	8	2.5
3	203	50.0	6	2.0
4	162	78.0	8	2.0
5	162	62.4	6	3.0
6	162	50.0	10	2.5
7	130	78.0	6	2.5
8	130	62.4	10	2.0
9	130	50.0	8	3.0

The steps which had followed to conduct these experiments are listed below: [8]

While recording angle and torque readings, specimens had twisted until they fail.

1. Mount the specimen in the chucks as follows:
   a) Zero the torque gage.
   b) Align the flats on one end of the specimen in the motor-side chuck. Tighten the chuck firmly.
   c) Use the motor to align the flats on the other end with the torque sensor chuck. Hand tighten.
   d) 'Bounce' the motor back and forth while continuing to tighten the chuck by hand. (Don't overstress the specimen while doing this!)
   e) When you can no longer turn the chuck by hand, tighten it firmly with the key.
   f) Turn the hand crank to bring the torque reading back to zero.
   g) Zero the angle indicator wheel.
2) Measure and record the distance between chucks on the worksheet.
3) Turn the hand crank CW. Record torque for every 2^0 angle of twist.
4) Do not re-set the angle indicator. Continue turning using hand wheel at slow speed.
5) Record torque at 2^0 intervals.
6) Start the motor after plastic deformation till the failure occurs.
7) After the specimen breaks, record the peak torque and angle at failure on the worksheet.
8) Measure and record the length of the twisted part of the specimen.
9) Remove the specimen and repeat steps 1 through 8 for each experiment.

Fig. 1 Mild steel Specimens before failure

Fig. 2 Mild steel Specimens after failure

Fig. 3 Digital torsion testing machine 200N-m

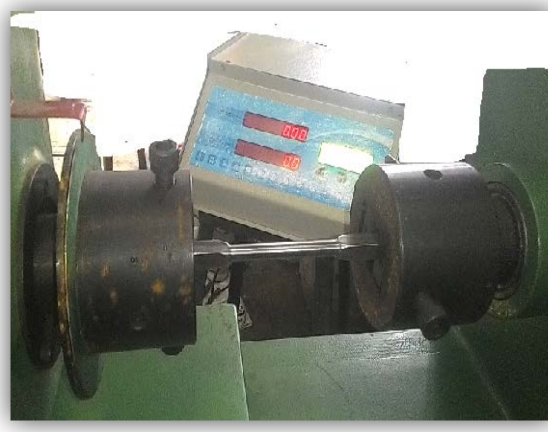

Fig.4 Specimen mounted between chucks

III.RESULTS

As per the design of experiment, each experiment with aforesaid specimen dimensions was performed. Three specimens were prepared so as to minimize variation for each of total length, useful length, outer diameter and fillet radius. Overall 27 specimens were prepared and torsion test was performed on digital torsion testing machine. Modulus of rigidityfor each trial has been found from shear stress vs. shear strain graph as responses in the respective experiments.

Experimental data comprising of values of specimen dimensions at each level in the respective experiments and their corresponding responses were shown in Table 5. The modulus of rigidity is taken as of Lower the better type. The S/N ratio for the Lower the better type of response can be computed as:

TABLE V MODULUS OF RIGIDITY FOR EACH TRIAL AND S/N RATIO AGAINST TRIAL NUMBERS

Expt. No.	Modulus of rigidity (GPa)				S/N ratio	MEAN
	1	2	3	Avg.		
1	77.5	77.12	77.7	77.44	-37.7793	77.44
2	76.95	76.75	77.3	77.00	-37.7298	77.00
3	79.90	80.20	79.90	80.00	-38.0618	80.00
4	79.00	77.71	77.30	78.00	-37.8419	78.00
5	78.00	77.20	77.61	77.60	-37.7972	77.60
6	79.21	79.32	79.27	79.27	-37.9822	79.27
7	78.13	78.14	78.13	78.13	-37.8564	78.13
8	77.56	77.23	76.9	77.23	-37.7557	77.23
9	79.85	78.96	79.29	79.37	-37.9931	79.37

n = -10 Log_{10} [mean of sum of squares of measured data]

$$n = -10\log_{10}\left(\frac{1}{R}\sum_{j=1}^{R} y_j^2\right) \quad \text{--------} \quad (2)$$

Where y_j = is the response value, under the trial conditions repeated R times. The mean response refers to the average value of the performance characteristic for each variable at different levels. Number of methods have been suggested by Taguchi to analyze the data namely observation method, ranking method, column effect method, ANOVA, S/N ANOVA, plot of average response curves, interaction graphs etc.[9]. However, in the present investigation the following methods have been used asPlot of average response curves, ANOVA for raw data, and ANOVAfor S/N data and S/N response graphs[10].The modulus of rigidity value of each trial and S/N ratio against trial numbers are shown in table V.

IV.EFFECT OF SPECIMEN DIMENSIONS

The average values and signal to noise ratios of modulus of rigidity for each of the nine experiments were calculated from the experimental data given in Table 4. The modulus of rigidity found minimum for the specimen dimensions with total length is of 203 mm,useful length 62.4 mm, outer diameter 8 mm and fillet radius 2.5 mm.The modulus of rigidity and average values for each parameter at levels 1, 2 and 3 for S/N data and raw data are displayed in Table 6 and Table7 respectively. The graph showing the effects of specimen dimensions on S/N ratio and effects of specimen dimension on Modulus of rigidity are shown in fig. 5 and fig.6 respectively.

TABLE VI RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS (SMALLER IS BETTER)

Level	Total length (LT)	Useful length (LU)	Outer diameter	Fillet radius (R)
1	-37.87	-38.01	-37.91	-37.86
2	-37.85	-37.76	-37.85	-37.86
3	-37.86	-37.82	-37.83	-37.86
Delta	0.02	0.25	0.08	0.01
Rank	3	1	2	4

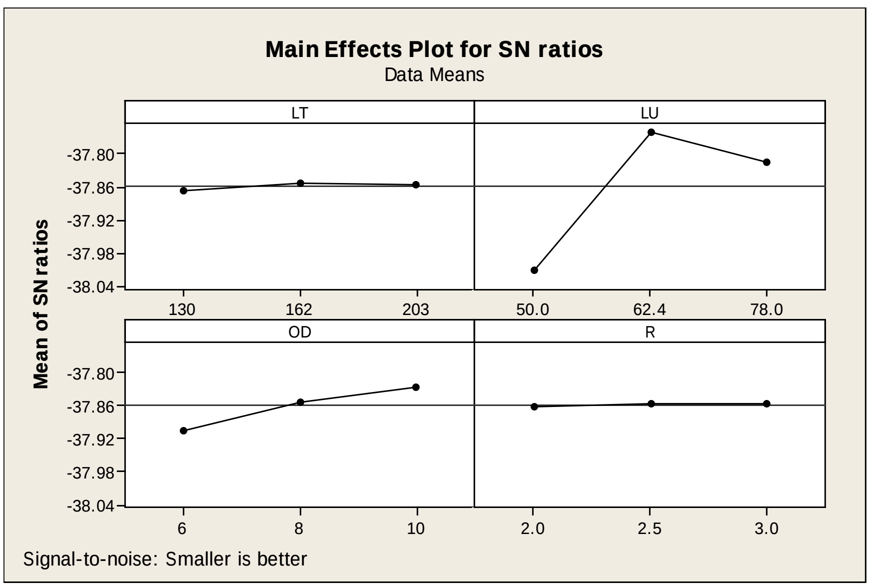

Fig. 5 Effects of specimen dimensions on S/N ratio (main effects)

The optimum mean of the response characteristics can be predicted at the optimal specimen dimensions. In order to predict the optimum mean, only significant dimensions are taken into consideration. The ANOVA identifies the significant dimensions. Suppose, dimensions A and B are significant and A2B2 (second level of both A and B) is the optimal specimen dimension. Then, the mean at the optimal dimension (optimal value of the response characteristic) is estimated as:

$$\eta_{opt.} = \overline{T} + (\overline{A}_2 - \overline{T}) + (\overline{B}_2 - \overline{T})$$

$$= \overline{A}_2 + \overline{B}_2 - \overline{T} \text{---} \quad (3)$$

Where,

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

$\overline{A}_2, \overline{B}_2$ = average values of response at the second levels of dimensions A and B respectively.

It may sometimes be possible that the predicated combination of specimen dimension levels (optimal specimen dimension) is identical to one of those in the experiment.

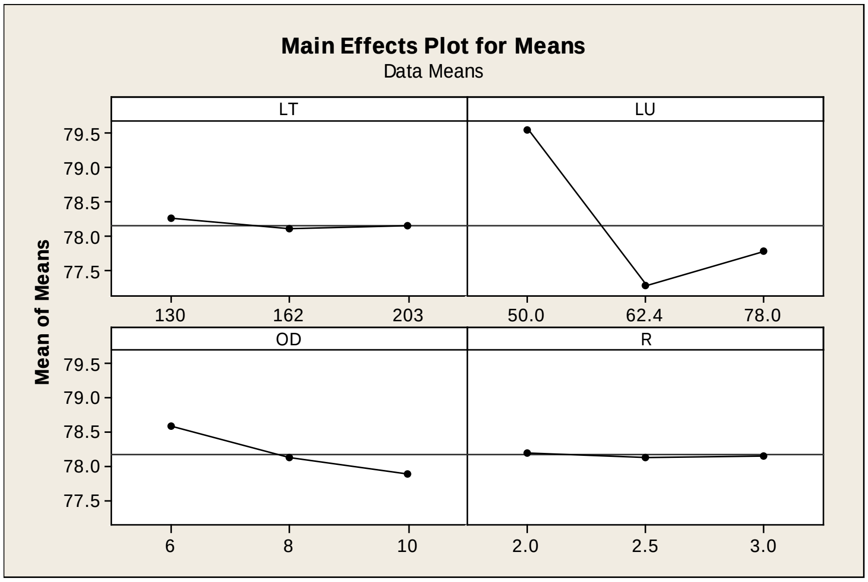

Fig. 6 Effects of specimen dimensions on modulus of rigidity (raw data)

TABLE VII RESPONSE TABLE FOR MEANS

Level	Total length (LT)	Useful length (LU)	Outer diameter (OD)	Fillet radius (R)
1	78.24	79.55	78.58	78.20
2	78.11	77.28	78.12	78.13
3	78.15	77.78	77.87	78.14
Delta	0.14	2.27	0.70	0.06
Rank	3	1	3	4

After analyzing the graphs in Fig. 5 and 6, it is observed that the modulus of rigidity increases with increase in useful length and decreases with increase in outer diameter. The ANOVA for modulus of rigidity is shown in Table VIII.

TABLE VIII ANOVA FOR MODULUS OF RIGIDITY

Source	**DOF**	**Seq SS**	**Adj SS**	**Adj MS**	**% Contri.**
Total Length	2	0.0321	0.0321	0.016	0.3523
Useful Length	2	8.3454	8.3454	4.1727	91.5989
Outer Diameter	2	0.5821	0.5821	0.291	6.3891
Fillet Radius	2	0.1513	0.1513	0.0756	1.6606
Error	0	-	-	-	-
Total	8	9.1108	-	-	100.00

In the present investigation, the four factors are considered at three levels of each factor. Thus,

The total DOF = Number of runs – 1
Main effective DOF for factor = Number of factor level – 1
Now, the residual error can be given as,
Error = Total DOF – Sum of DOF for all factors
There are four factors, therefore
Error = 8 – (2+2+2+2)
Error = 0

Zero degrees of freedom for error cause the calculations to fail as follows. Each value in the Adj MS column is calculated by dividing the values in the Adj SS column by the corresponding values in the DOF column. But, the Adj MS for Residual Error, ‘f’ values and ‘p’ values, cannot be calculated because it is impossible to divide anything by 0 degrees of freedom. So in this case, to find the percentage contribution of each factor, General linear model ANOVA is done, which will calculate the Seq SS, Adj SS and Adj MS. By using these values the percentage contribution of each factor in deciding modulus of rigidity can be calculated.

To study the significance of the specimen dimension variables on the value of modulus of rigidity, analysis of variance (ANOVA) was performed as shown in Table8. It is observed that useful lengthand outer diameter affect the modulus of rigidity value significantly. Table6 and 7 shows the average of each response characteristic (S/N data, means) for each dimension parameter level. These Tables give the information about the ranks based on delta statistics, which compare the relative magnitude of effects. The delta statistic is the highest value,minus the lowest average for each parameter. The Minitab16©software tool is used to analyze these specimen dimension parameters. The ranks are assignedbased on delta values such as the rank 1 to the highest delta value, rank 2 to the second highest and so on. The ranks indicate the relative importance of each specimen dimension parameter to the response. The ranks and the delta values are shown in Table 7, indicates the useful length the greatest effect on modulus of rigidity value compared to other specimen dimensions.

V. DISCUSSIONS

It is observed from the graphs shown in Fig. 5 (Effects of specimen dimensions on S/N ratio) and Fig. 6**(**Effects of specimen dimensions on modulus of rigidity) that the modulus of rigidity increases with increase in useful length and decreases with increase in outer diameter. However, the useful length and outer diameter are preferred according to ASTM standard give correct results in torsion testing.

The factors associated with torsion tests are: the homogeneity of the material, the strain measurement, the specimen geometry, and the determination of the shear stress-strain curve from the experimental torque versus angle of twistcurve.These factors are explained as follows:

1. The material homogeneity: If the material is not homogeneous, non-uniform deformation will occur, leading to regions that remain almost undeformed while plastic deformation occurring in the remaining part of the specimen. Thestrain concentration will lead to an early development of shear band localization in the specimen. This is a very seriousproblem, especially when long gage-length specimens are used [6].
2. The strain measurement: An important problem associated with the torsion test and the combined axial-torsion test isthe strain measurement. The method does not lead to accurate strain measurements due to the geometry of the specimenwhich has enlarged ends.
3. The specimen geometry: Torsion tests have been conducted by use of tubular specimen. Tubular specimens are used in most of research. The advantages for this type of specimen are: (a) accurate shear strainmeasurement may be obtained because of the long gage section that this type of specimen has; (b) accurate strainmeasurements may be obtained in axial and hoop strains; (c) the specimen may be used for combined axial-torsionaltesting; (d) the specimen is suitable for test involving unloading/reloading/cyclic loading; and (e) the specimen may beused for investigation of shear band localization. The axial strain mentioned in (b) is greatly influenced by thespecimen geometry Solid shafts can achieve very large strain without buckling
4. The determination of shear stress-strain curve: It uses a theory to convert the torque versus angle of twist curve intothe shear stress-strain curve. Most of the theories such as Nadai or Canova et al. do not account forlength change of the specimen subjected to torsion and, therefore, do not lead to accurate results for free-end torsion.Although the method can be used to obtain accurate shear stress-strain curve for the fixed-end torsion test. Therefore, the free-end torsion of tubular specimens is still a practical test for the determination of true shearstress-strain curve. For this purpose, experimental data for axial and hoop strains are also needed. Based on the Nadaimethod, Wu et al. developed a method which, by accounting for the axial and hoop strains, provides atrue shear stress-strain curve from the free-end torsion test. This true shear stress-strain curve is consistent with thatdetermined from the fixed-end torsion test [7].

VI.CONCLUSIONS

The experiments were conducted on different specimen dimensions using L9 orthogal array by Taguchi. The specimens were manufactured in close tolerances to minimize the variations in dimensions.The specimens were tested for investigation of modulus of rigidity on digital torsion testing machine having capacity 200 N-m. The following conclusions are drawn from the study.

1. The useful length, outer diameter and total length significantly affect the modulus of rigidity whereas the fillet radius is not so significant.
2. Determination of true shear stress-strain curve affects significantly on investigation of modulus of rigidity.
3. Strain hardening coefficient and strain rate parameter affects on determination of modulus of rigidity.
4. It is observed from the study that, the modulus of rigidity is minimal with total length 203 mm, useful length 62.4 mm, outer diameter 8 mm and fillet radius 2.5 mm.

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