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THE EFFECT OF THE ANGLE AND DIMENSIONS OF A CROSS-SECTION SPECIMEN ON THE TORSIONAL STRENGTH OF AISI 1020 SQUARE STEEL SHAFT

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Abstract. The unknown torsional strength due to the inconsistency of the angles and dimensions of the square cross-section of AISI 1020 steel specimens in the torsion test is the problem encountered. The research method included: preparation of square AISI 1020 steel specimens measuring 6 mm x 6 mm x 160 mm, measurement of 2 diagonal angles of the cross section of the specimen and dimensions of the cross section at 5 observation points along the specimen receiving torsion loads, torsion testing of specimens, analysis of torsion test results data, and drawing conclusions. The results of the study affect the angle and dimensions of the specimen cross-section on the torsional strength of the AISI 1020 steel square shaft which has a greater value at the angles of 89° and 91° than 90° which with an angle of 89° at dimensions of 5.96 mm x 5.96 mm has a torsional strength of 412 MPa, while at an angle of 90° with dimensions of 5.96 mm x 5.96 mm it has a torsional strength of 359 MPa, and for an angle of 91° in dimensions of 5.95 mm x 5.95 mm has a torsional strength of 402 MPa. The average torsional strength is achieved in the range of 351 to 397 MPa, at an angle of 89° the torsional strength increases by 46 MPa or around 13.1 %, and at an angle of 91° the torsional strength increases by 43 MPa or around 12.3%.

Keywords: Specimen cross-sectional angle, Specimen cross-sectional dimensions, AISI 1020 steel, square shaft, Torsional strength.

1. INTRODUCTION

Improvement of material toughness due to hardening and tempering has been carried out on low carbon steel with pressurized water, air and oil [1]. By heat treatment the toughness of low carbon materials can be increased. Fabrication of metal materials for the industrial world is carried out by forging, rolling and extruding in which rolling is carried out by clamping the plate between two rollers from the pressure roller and the main roller which rotates in opposite directions, so that it can move the plate [2]. In rolling it cannot be guaranteed to produce a cross section that is truly 90° angled with uniform rectangular dimensions. The rotary bending test obtained the maximum safe limit value for the torsional stress of 283.95 MPa which meets the requirements for ship shaft materials [3]. It is important to know the torsional strength of the shaft prior to use so as not to exceed the specified allowable value. Research on hardened S45C steel showed that the torsional strength was 425.67 MPa with the dominant ferrite phase microstructure and the tempering results were 392.7 MPa lower with the dominant pearlite phase microstructure [4]. Shaft heat treatment provides increased torsional strength. The results showed that ST 60 steel for the propeller shaft with hardening heat treatment followed by tempering had a torsional strength of 737.72 MPa [5]. ST 60 steel has higher torsional strength than S45C steel. Coating material that is softer or less rigid than the shaft material can reduce the maximum value of the stress on the shaft cross section [6]. The softer nature of the coating material contributes to lowering the stress on the shaft being coated. The torsional moment of ST 37 is lower than that of ST 90, then the torsional moment of ST90 is lower than that of VCN [7].

The torsional moment reflects the torsional strength of the material being tested for torsion. Low carbon steels produced in the largest quantities are included in the low carbon classification which generally contain less than 0.25% by weight C and are unresponsive to heat treatment intended to form martensite, reinforcement is done by cold working. The microstructure consists of the constituents ferrite and pearlite which as a result, the alloy is relatively soft and weak, but has outstanding ductility and toughness [8]. Low carbon steels are very ductile and cannot be heat treated, except hardened by carburizing. The increase in stiffness in torsion of a flat bar is highly dependent on the width and thickness of the flat bar, separation/expansion distance, and angle of twist. The torque angle resulting from the bonded bending of 2 plates whose ends are welded for a length of 528 mm, a width of 30 mm to 60 mm for a thickness of 3 mm and 6 mm achieves a total torque of around 5.3% to 10.1% [9]. Twisting of flat reinforcement is affected by its dimensions, separation distance and angle of twist. The GGM 90 W motor type in the torsion testing machine modification has a torque of 408.9 Nmm and a rotation output of 124 rpm [10]. The speed of the manual motor drive modification is relatively unstable compared to the drive using an electric motor in a torsion testing machine with a constant rotation.

The results showed that ST 41 steel with quenching heat treatment had a torsional strength of 448.65 MPa [11]. Medium carbon steel can be heat treated, so that the strength can be increased after heat treatment. The results of the ABS, PET and PLA torsion tests showed that the highest torque of acrylonitrile butadiide styrene (ABS) was achieved at 230 ^oC compared to 240 ^oC, 250 ^oC and 260 ^oC; for PET material, the highest torque is achieved at a temperature of 235 ^oC compared to temperatures of 220 ^oC, 230 ^oC and 240 ^oC; and for polylactic acid (PLA) materials the highest torque is achieved at a temperature of 215 ^oC compared to temperatures of 200 ^oC, 205 ^oC and 210 ^oC [12]. The molding temperature of ABS, PET and PLA materials affects the torque or torsional strength of the plastic material. One of the main problems in the design of machine components that receive torsional stresses is determining the optimal shape and dimensions so that they can withstand the torsional loads they receive [13]. Optimal design of a component can save costs, volume of materials and duration of the processing process.

The results of the geometry and modeling of the torsion test specimen according to ASTM E-143 show that the stress distribution that occurs on the surface area of the specimen is not significant between 2.879e+09 Pa and 2.973e+09 Pa [14]. The stress distribution that occurs on the surface of the specimen area is influenced by the geometry and modeling designed in the simulation. The standard test equipment has maximum strength when the specimen breaks at an angle of 130^o third round with a torsional moment of 3.37 Nm, and the design test equipment has maximum strength when it breaks at 230^o fourth round with a torque reading of 3.65 Nm. The maximum torsional strength is a difference of 7.67% from 3.65 Nm [15]. If there is a difference in the torsional strength results between the manual torsion testing machine and the electric motor drive, it is necessary to adjust the length of the arm and calibrate it. The results of the three-point bending test and torsion test show that the stress distribution on the rectangular hollow cross-section (RHS) shows that the use of direct-forming with welding of edge (DFW-RHS) as a reinforcing beam has higher stiffness compared to direct-forming (DF-RHS), which means that under identical loading, direct forming (DF-RHS) with t = 1.93 mm has the same stiffness as direct forming with edge welding (DFW-RHS) with t = 0.7 mm, that is, the potential for reducing metal materials is 62% [16]. With a special shape profile that increases stiffness can save the use of materials to obtain the same stiffness value.

2. METHODS

Torsion test on a specimen is carried out to determine the plasticity of a material. The specimens used in the torsion test are rods with circular/square cross-sections for the simplest cross-sectional shapes, so they are easy to measure. The specimen is only subjected to a twisting load at one of the two ends. With torsional loading the specimen is forced to twist until it breaks, the recorded torsional force value is calculated to be the torsional moment and the twist angle value is used to plot the twisting performance curve. From the torsional moment, the torsional stress acting on the specimen can be calculated. The existence of specimens in the torsion test was chosen as a square shape which is not guaranteed to have an exact 90^o angle and the dimensions along the torsion area are also not guaranteed to be uniform, therefore in this study it was observed to analyze its effect on the torsional stress that occurs. The measurement of the right angle was carried out in a diagonal position with 5 (five) times replication along the torsion area and similarly for non-uniformity of the dimensions of the height and width of the cross-section was measured with 5 (five) times of replication as well.

In the plastic region, the relationship between the torsional moment and the torsion angle is non-linear, the shear stress can be calculated using Formula (1) [11].

$$\tau = \frac{T.c}{J} \tag{1}$$

Where T: torsion moment measured during torsion test, T = force x torsion arm = F. l; c: distance to the outermost fiber for a square cross section or the radius of a circle for a cylindrical cross section.
Polar moment of inertia for cylindrical, square and triangular cross sections [12].

$$J = \pi D^4/32 \text{ for the cylindrical cross section} \quad (2)$$

$$J = (bh^3+b^3h)/12 \text{ for square cross section} \quad (3)$$

$$J = (bh^3+hb^3)/12 \text{ for triangular cross section} \quad (4)$$

Shear Elastic Modulus, G:

$$G = \tau / \gamma = T.L/J.\ \theta \quad (5)$$

Where: τ: shear stress; γ: shear strain; T: torsional moment (torque); L: length of shaft subjected to twist; J: polar moment of inertia; and θ: the angle of internal twist (the circumference of a circle is 360° or 2π, with units conversion 360/2π = 360 x 3.14 = 57.3 in degrees = 1 radians) is shown in Equation (5).

The specimens used for testing are low carbon steel types following the ASTM (American Society of Testing and Materials) standard type E-143-02 Standard Test Method for Shear Modulus at Room Temperatures is shown in Figure 1 and Table 1 [17].

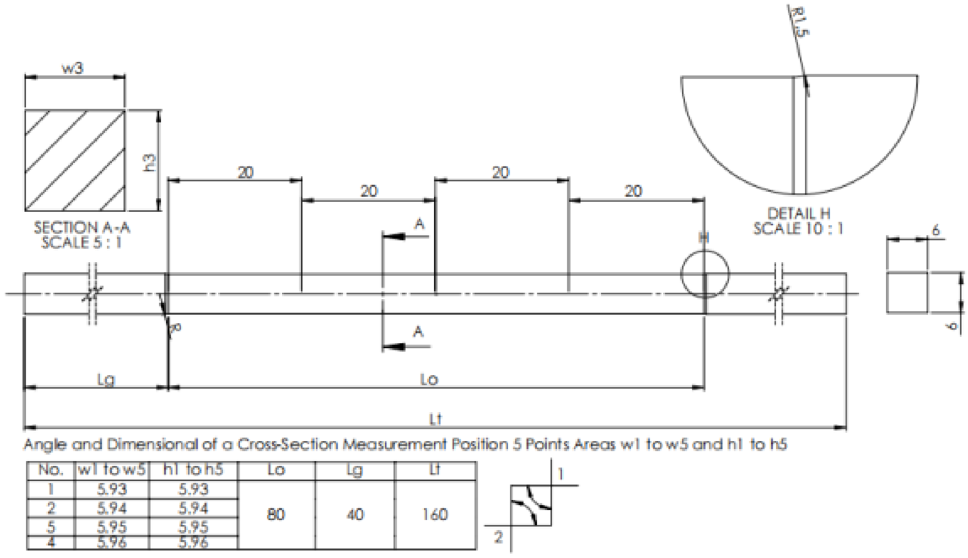

Figure 1. The shape of the torsion test specimen [17]

Table 1. Twist Test Specimens

Test Specimens	Specimen Dimensions (mm)					
	Do	Lo	R	Dg	Lg	Lt
ASTM E143-13	5.93, 5.94, 5.95 dan 5.96	80	1.5	6.64	39	160

The AISI 1020 steel selected for the study contains 0.20% carbon which can be designated as low carbon steel and its chemical composition is shown in Table 2.

Table 2. Chemical Composition of AISI 1020 Steel

No.	Element	Content (wt%)
1	Carbon (C)	0.142
2	Silicon (Si)	0.210
3	Manganese (Mn)	0.551
4	Phosphorous (P)	< 0.0100
5	Sulphur (S)	0.027
6	Chromium (Cr)	0.028
7	Nickel (Ni)	0.061
8	Molybdenum (Mo)	0.010
9	Copper (Cu)	0.093
10	Aluminium (Al)	< 0.0050
11	Titanium (Ti)	0.0030
12	Ferro (Fe)	98.85

Specifications for torsional test specimens made of AISI 1020 steel with dimensions of 6 mm x 6 mm x 160 mm with mechanical properties is shown in Table 3. The test is carried out with 4 sizes in the range from minimum to maximum of 5.93, 5.94, 5.95, and 5.96 mm with angles of 89^o, 90^o and 91^o with 3 replications, so that the number of torsion test specimens is thirty-six.

Table 3. Mechanical Properties

Property	Tensile Strength	Yield Strength	Modulus of elasticity	Poisson ratio	Elongation at Break	Hardness
Metric	420 MPa	350 MPa	186 GPa	0.29	15%	110-121 BHN

Arrangement of research equipment was carried out with the following procedures: (1) cutting of low carbon steel AISI 1020 in a square shape measuring 6 mm x 6 mm x 160 mm in a total of thirty six specimens; (2) cleaning the specimen from dust, rust and checking its alignment; (3) marking a distance of 20 mm for 5 points in the torsion area, (4) measuring the dimensions (height and width) of the section using a vernier caliper, (5) measuring at 2 angles with the bevel protractor at the diagonal position of the section at 5 marked points; (6) recording the results of measurement of dimensions and angles into the specimen data sheet; (7) setting the torsion testing machine by adjusting the length of the specimen to 160 mm by installing 2 auxiliary tools in the form of 3 legs with a square hole measuring 6 mm x 6 mm which can be entered at both ends of the specimen to ensure that slippage cannot occur when the specimen is twisted, and (8) clamping the two ends of the specimen to a depth of 20 mm from both ends by tightening the two chucks contained in the torsion testing machine scheme is shown in Figure 2.

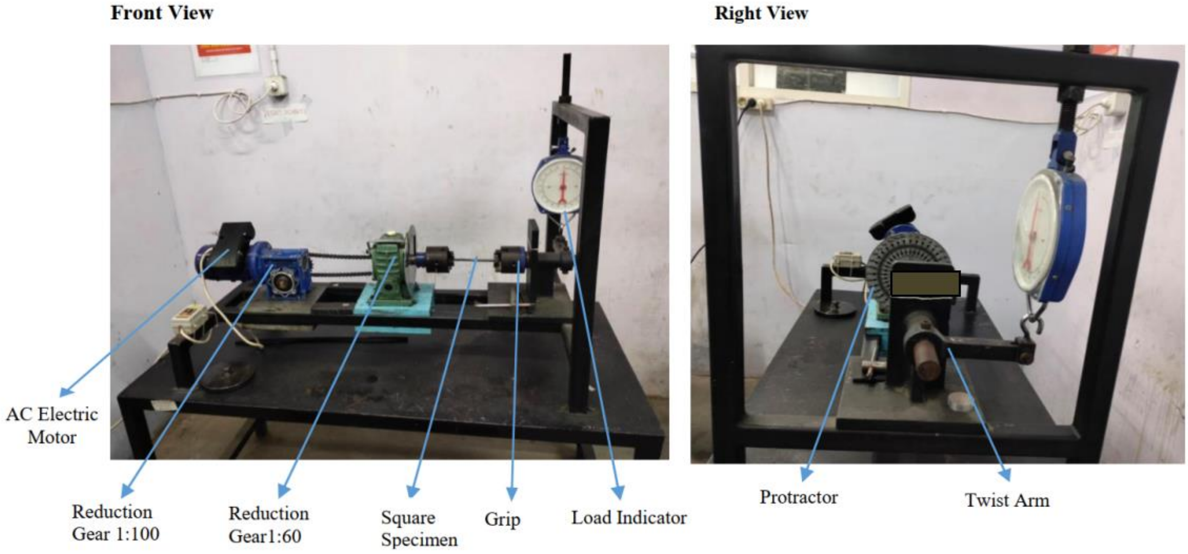

Figure 2. Schematic of torsion testing of square specimens

3. RESULTS AND DISCUSSION

The specimen before the torsion test is shown in Figure 3 and the specimen after the torsion test is shown in Figure 4.


Figure 3. Torsion test specimens before testing


Figure 4. Torsion test specimens after testing

Table 4. The torsional strength results from square shaft torsion tests

Specimen cross-sectional angle (°)	Specimen cross-sectional dimensions (mm)	Torsional strength (MPa) Replication		
		1	2	3
Angle 89°	5.93 x 5.93	394	395	382
	5.94 x 5.94	403	380	405
	5.95 x 5.95	380	401	414
	5.96 x 5.96	387	412	412
Angle 90°	5.93 x 5.93	354	354	344
	5.94 x 5.94	331	343	364
	5.95 x 5.95	330	351	330
	5.96 x 5.96	329	359	350
Angle 91°	5.93 x 5.93	405	395	405
	5.94 x 5.94	381	405	393
	5.95 x 5.95	402	391	402
	5.96 x 5.96	400	389	389

The torsional strength of AISI 1020 steel in the cross-sectional dimensions for the cross-sectional angles of 89°, 90° and 91° are shown in Figure 5.

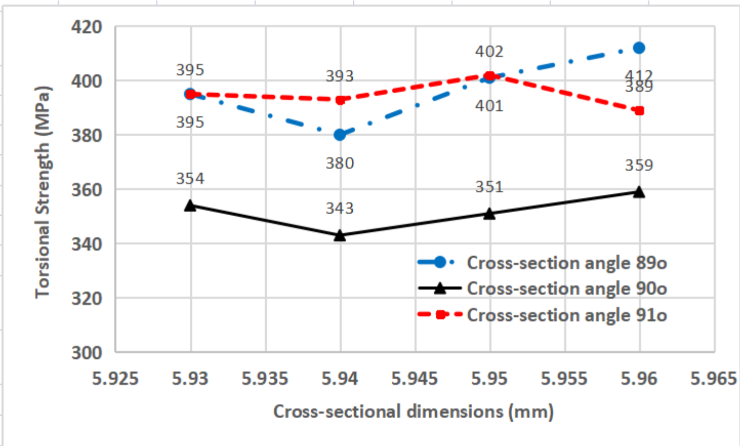

Figure 5. The torsional strength of AISI 1020 steel for the angles of 89°, 90° and 91°

The torsional strength of AISI 1020 steel at an angle of 89° and dimensions of 5.94 mm x 5.94 mm has the lowest torsional strength value at a torsional angle of 720° worth 380 MPa and at dimensions of 5.96 mm x 5.96 mm it has the highest torsional strength at a torsional angle of 720° worth 412 MPa is shown in Table 5 and Figure 6.

Table 5. The torsional strength of AISI 1020 steel at cross-section angles at 89°

No.	Specimen cross-sectional Dimensions (mm)	Twisting Moment			Torsional Strength (MPa)	Maximum Twist Angle (°)
		(kg.m)	(N.m)	(N.mm)		
1	5.93 x 5.93	2.47	24.7	24650	395	680
2	5.94 x 5.94	2.54	25.4	25375	380	720
3	5.95 x 5.95	2.61	26.61	26100	401	720
4	5.96 x 5.96	2.61	26.61	26100	412	720
				Average=	**397**	

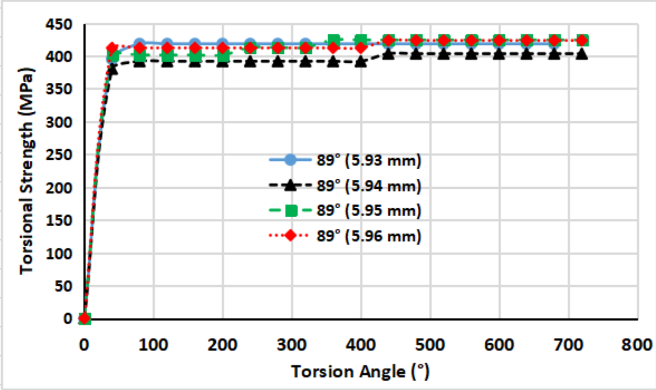

Figure 6. The torsional strength of AISI 1020 steel at a cross-sectional angle of 89°

The torsional strength of AISI 1020 steel at cross-section angles at 90° and dimensions of 5.94 mm x 5.94 mm has the lowest torsional strength value at a torsional angle of 760° worth 343 MPa and at dimensions of 5.96 mm x 5.96 mm it has the highest torsional strength at a torsional angle of 800° worth 359 MPa is shown in Table 6 and Figure 7.

Table 6. Torsional strength of AISI 1020 steel at an angle of cross section at 90°

No.	Specimen cross-sectional Dimensions (mm)	Twisting Moment			Torsional Strength (MPa)	Maximum Twist Angle (°)
		(kg.m)	(N.m)	(N.mm)		
1	5.93	2.47	24.7	24650	354	720
2	5.94	2.39	23.93	23925	343	760
3	5.95	2.47	24.7	24650	351	640
4	5.96	2.54	25.38	25375	359	800
				Average=	**351**	

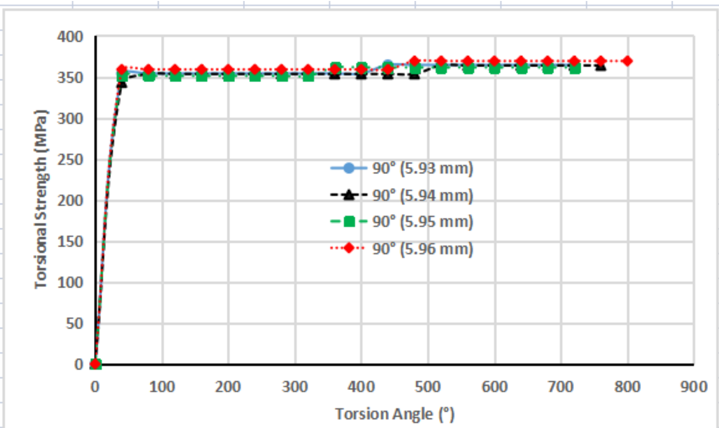

Figure 7. The torsional strength of AISI 1020 steel at a cross-sectional angle at 90°

The torsional strength of AISI 1020 steel at cross-section angles at 91o and dimensions of 5.94 mm x 5.94 mm has the lowest torsional strength value at a torsional angle of 760° worth 393 MPa and at dimensions of 5.95 mm x 5.95 mm it has the highest torsional strength at a torsional angle of 720° worth 402 MPa is shown in Table 7 and Figure 8.

Table 7. Torsional strength of AISI 1020 steel at an angle of cross section at 91°

No.	Specimen cross-sectional Dimensions (mm)	Twisting Moment			Torsional Strength (MPa)	Maximum Twist Angle (°)
		(kg.m)	(N.m)	(N.mm)		
1	5.93	2.47	24.65	24650	395	720
2	5.94	2.47	24.65	24650	393	760
3	5.95	2.54	25.38	25375	402	720
4	5.96	2.47	24.65	24650	389	800
			Average=		**394**	

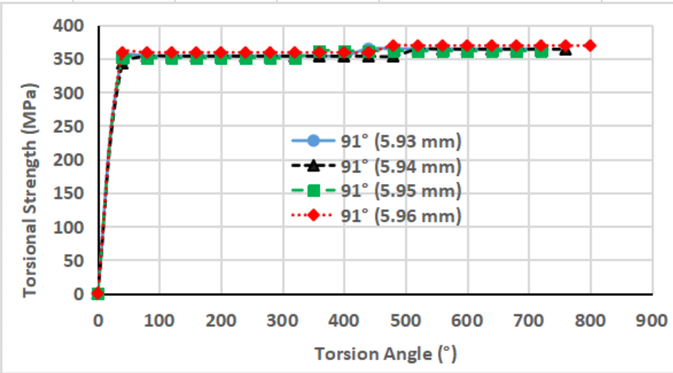

Figure 8. The torsional strength of AISI 1020 steel at cross-sectional angle at 91°

Overall the torsional strength of AISI 1020 steel at cross-section angles at 89° to 91° has a range of values from 343 to 412 MPa or an average of 381 MPa.

The torsional strength of AISI 1020 steel at cross-section angles is not 90° which at cross-section angles 89° increases by 397-351 = 46 MPa or about 13.1% and at cross-section angles 91° it increases by 394-351 = 43 MPa or about 12.3%. So the change in cross-section angles is not 90°, both with a 1° change increase the torsional strength by about 12%.

4. CONCLUSION AND SUGGESTION

The conclusions that can be drawn from the discussion of the torsional strength of AISI 1020 steel at cross-section angles 89°, 9^{0o} and 91° are:
1) Torsional strength is achieved in the range of 351 to 397 MPa;
2) At an angle of 89° the torsional strength increases by 46 MPa or around 13.1 %; and
3) At an angle of 91° the torsional strength increases by 43 MPa or around 12.3 %.

Follow-up suggestions for conclusions include:
1) It is necessary to conduct research on shaft materials other than low carbon steel; and
2) It is necessary to conduct research on the shaft material in the shape of a pipe, either rectangular or cylindrical.

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