

Effects of Notch Angle and Notch Radius on Mechanical Properties of Low and Medium Carbon Steels

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Abstract

Steels of different grades are widely used in manufacturing industries in producing machine parts and components. Properties such as low cost, ductility, and malleability have made low and medium carbon steels unique and therefore there are many areas of applications. However, in service these properties are affected when there is a presence of notch. In this study, the behaviour of notched steel bars were investigated under tension, torsion and impact at different notch angles (30°, 45° and 60°) and notch tip radii (0.5 mm, and 1.0 mm). The results of the investigation showed that variation in angle and tip radius of the notch area affected the absorption energy, twisting resistance and tensile properties of the steel bars. It was noticed that samples with greater notch angle and notch tip radius have higher absorption energy. It was observed that larger notch angle and notch tip radius required higher values of torque before twisting can occur.

Keywords

Mechanical properties, mild steel, notch angle, notch radius, stress concentration

1. Introduction

Most of engineering components with various geometries have at least one notch in their structure Kobayashi, et al., (2019). Designers usually use notches because of some necessary design parameters, such as minimizing

weight, increasing the moment of inertia, introducing manholes, transmitting power, etc. In the process of design, notch decreases the load-carrying capacity (LCC) of the components because of the notches and cracks on the metal Torabi & Kamyab, (2019). The components overtime fail due to the presence of these stress concentrators (notches) on them.

Zhao et al., (2019) investigated the notch effects on deformation of wurtzite aluminum nitrides (w-AlN) and amorphous aluminum nitrides (a-AlN) under tension using molecular dynamic simulation. The introduction of notch resulted in an obvious reduction in strength and ductility of both samples (i.e. w-AlN and a-AlN). Unlike w-AlN, lower strength sensitivity to the notch and improved fracture toughness were observed in a-AlN. They concluded that the effect of notch sizes (tip radius and depths) revealed that w-AlN is a notch weakening material, whereas, the deformation of a-AlN is less sensitive to either the notch tip radius or the depth.

Singh et al., (2016) experimentally examined the influence of notch root radius and strain rate on the fracture behavior and tensile properties of Tungsten inert gas (TIG)-welded 6061 aluminum alloy under uniaxial static loading. Their findings show that increasing the notch root radius correspond to an increase in yield strength as well as the ultimate tensile strength and thereafter decrease on further increase in the notch root radius. The strength, however, decreases at higher strain rates because the notch propagated through the base metal instead of the weld metal zone. Hence, they concluded that the strength and toughness of the welded component with notch were higher than welded component without notch.

Torabi et al., (2019) conducted an investigation on the effect of notch angle, specimen diameter and notch diameter on fracture toughness of Al 7075 T6 Alloy. Their findings revealed that an increase in notch angles led to increasing fracture toughness of the material. They also concluded that as specimen diameter along with notch diameter increases, the value of fracture energy increases while the ultimate tensile strength of the material gets decreased. Ayatollahi & Torabi, (2010) investigated both experimentally and theoretically study of tensile fracture in notched polycrystalline graphite specimens under pure I-mode loading conditions. Their findings revealed that three sets of experimental results were consistent (i.e. rounded-tip V-

notched Brazilian disk (RV-BD); rounded-tip V-notched semi-circular bend (RV-SCB) and rounded-tip V-notched Brazilian disk (RV-BD) specimens) and these specimens were said to be used to determine the notch fracture toughness in isotropic polycrystalline graphite materials. The MS criterion was also extended to rounded-tip V-notched domains in order to estimate the fracture toughness of notched graphite components. It was shown that the experimental results were in very good agreement with the results estimated by the mean stress (MS) criterion. It was also found that the notch fracture toughness is not a constant material property and depends on the notch geometry parameters i.e. the notch angle and the notch tip radius.

Since notches and cracks are hardly do away with in engineering practice, it is the responsibilities of designers to ensure that materials with notch are used longer in service, hence appropriate mechanical test must be done to evaluate the characteristics of such materials Rittel, et al., (2014). Therefore, there is a need to study the effect of notch angles and tip radius on the mechanical properties of low and medium carbon steels.

2. Experimentation

2.1 Materials and methods

The materials used for this study were low carbon steel (LCS) and medium carbon steel (MCS). These materials were selected because of their wide range of applications in construction industries Antunes et al., (2019). The chemical composition of the materials (Table 1) was determined using spectrometer model AFS 200T.

Table 1 Chemical Composition of the Samples

Sample	% wt C	% wt Si	% wt Mn	% wt S	% wt P	% wt Cr	% wt Ni	% wt Cu	% wt Fe
Low Carbon Steel	0.219	0.169	0.481	0.067	0.057	0.184	0.088	0.245	98.478
Medium Carbon Steel	0.370	0.217	0.794	0.058	0.069	0.142	0.139	0.398	97.803

2.2 Experimental method

Sample preparation for Impact, Torsion and Tensile tests (Fig. 1) were carried out following ASTM specifications. The impact test according to ASTM E23-16b was carried out on Avery-Denison Izod impact testing

machine. The samples were prepared with gauge length of 46 mm, diameter of 10 mm, and notch tip radii of 0.5 mm and 1.0 mm with varied notch angles of 35°C, 45°C and 60°C on the two steel samples. According to ASTM F383-15, the Torsion test carried out on sample length of 100 mm, gauge length of 46 mm and radius of 5 mm. The tensile sample and test were prepared based on ASTM E8/(E8M-16), with gauge length of 32 mm, width of 6 mm and radius of 5 mm. The test was carried out on Testometric Universal Testing Machine (UTM) model FS-50AT with maximum load capacity of 50KN.

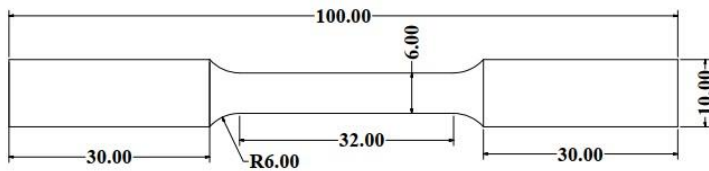


Figure 1 Tensile Test sample specification for the work

Notched sample (Fig. 2) was prepared with the aid of 30° and 45° angular files and chisel. The required notch depth (i.e. 2 mm) was measured and two different files having tip radius of 0.5 mm and 1.0 mm for each angle were used.

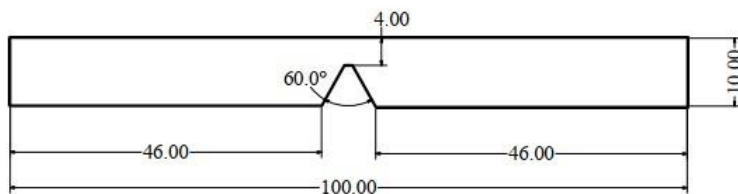


Figure 2 Schematic of the notched sample

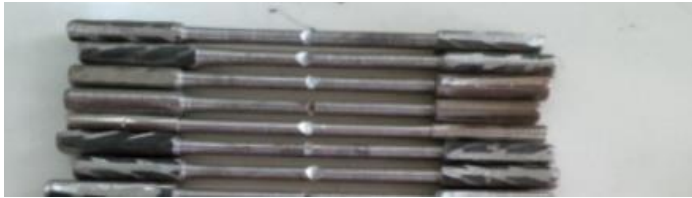


Figure 3 Photograph of the notched Samples

Izod impact testing machine was used for this research. The arm of the machine was allowed to swing freely to ensure freedom of movement of the striker. Each sample was clamped to the anvil of Izod impact testing machine. The pointer was set to zero energy position and the striker was released from a fixed height throughout the procedure Naquiuddin, et al., (2017). The energy absorbed by each sample was recorded as indicated by the pointer on the scale. The sample for the Torsion was gripped on torsion testing machine using hexagonal sockets. Both ends of the sample were fitted to input and torque shafts and reading on the torque meter was set to zero. Twisting the sample at strain increment of 0.5 was made until failure occurs. Tensile sample prepared according to ASTM standards Altenhof, et al., (2004).

3. Results and Discussion

3.1 Impact Test

The results of the impact tests are shown in Tables 2, 3 and 4 for 30°, 45° and 60° notched angle respectively. It can be observed that the absorption energy in Joules increases with increase in notch radius and notch angles for the two carbon steels. This implies that the lower notch tips radius and smaller angles have the lowest absorption energy due to the fact that the sample has smaller area at the root tip which is easier for crack to be initiated unlike that of larger tip radius and larger notch angle which the crack initiation has larger area to cover before it can be initiated hence results to higher absorbed energy Atzori, et al., (2003) and Fatemi, et al, (2002). In furtherance to this observation, percentage carbon contents also play a major role in the behaviour of the materials because higher carbon contents increases the hardness of the material which makes the material stronger and hence, absorbed more energy before failure. Table 1 shows that low carbon steel has a carbon content of 0.219 %wt, medium carbon steel 0.370 %wt which

buttress this behaviour. Failure of the component occurs at the notched point due to impact loading, this occurs because of higher stress concentration at the notched point Callister and Rethwisch, (2012).

Table 2 – Absorption Energy at notch angle 30°

Absorption Energy (Joules)		
Notch tip radius (mm)	Low Carbon Steel	Medium Carbon Steel
0.5	101	102
1.0	104	105

Table 3 – Absorption Energy at notch angle 45°

Absorption Energy (Joules)		
Notch tip radius (mm)	Low Carbon Steel	Medium Carbon Steel
0.5	102	105
1.0	105	109

Table 4 – Absorption Energy at notch angle 60°

Absorption Energy (Joules)		
Notch tip radius (mm)	Low Carbon Steel	Medium Carbon Steel
0.5	104	107
1.0	110	114

3.2 Torsion Test

Tables 5 and 6 show the results of Torsion test for the low and medium carbon steel used in this study. The results show that notch angle and notch tip radius influence the torsional strength of the two carbon steels tested. It can be seen (Table 5) that 60° notch angle and 1.00 mm notch radius gave breaks at 9.0° twist angle which means, the larger the notch angle and tip radius, the higher the torque that is required to twist the steel. Also, component failure occurs at the notched point due to twisting loading, this occurs because of higher stress concentration at the notched point Callister and Rethwisch, (2012). Lower notch tips radius and smaller angles have the lowest resistance to twisting forces due to the fact that the sample has smaller area at the root tip which makes it easier for crack to be initiated unlike that of larger tip radius and larger notch angle where the crack initiation has larger area to cover before it can be initiated hence results to more resistance

to twisting. The content of carbon in the steels equally has major role in the failure of the materials due to twisting Daemi and Majzoobi, (2011). This is because high carbon contents increases the hardness of the material which makes the material stronger and more resistance to twisting forces.

Table 5 Torsion Test for Low Carbon Steel (LCS)

TWIST (°)	TORQUE (Nm)					
	30° notch angle		45° notch angle		60° notch angle	
	0.5 mm	1.0 mm	0.5 mm	1.0 mm	0.5 mm	1.0 mm
6	1.9	2.6	2.2	3.0	4.8	5.2
12	2.2	5.4	4.0	6.6	8.0	9.0
18	6.6	7.4	10.4	11.0	9.0	12.2
30	11.6	12.4	13.2	14.8	14.0	14.4
36	14.0	15.2	15.6	15.8	15.6	16.1
42	15.6	16.0	16.3	16.9	16.0	16.8
48	16.2	16.6	16.8	17.6	17.2	17.5
54	16.8	17.0	17.3	18.0	17.8	18.2
60	17.3	17.8	17.9	18.4	18.4	18.8
66			18.1	18.8	18.8	19.2

Tensile test results for the samples are shown in Tables 7 and 8 respectively. It can be seen from (Tables 7 and 8). The 0.5 mm notch tips radius and 30° has ultimate tensile strength of 1493.612 N/mm² as against 1675.583 N/mm² for angle 30° and 60° due to the fact that the sample has smaller area at the root tip which will be easier for crack to be initiated except that of angle 45° which has high ultimate tensile strength for small notched tip radius which might have happened due to some errors in material preparation or due to the machine operator. Larger tip radius and larger notch angle amount to higher ultimate tensile strength because crack initiation will have to cover larger area before it can be initiated.

Table 6: Torsion Test for Medium Carbon Steel (MCS)

TWIST (°)	TORQUE (Nm)					
	30° notch angle		45° notch angle		60° notch angle	
	0.5 mm	1.0 mm	0.5 mm	1.0 mm	0.5 mm	1.0 mm
6	2.6	3.0		3.2	4.2	4.8
12	5.4	6.2	4.0	5.0	8.0	8.6
18	7.4	10.0	10.0	11.0	11.2	11.8
24	11.2	11.6	11.0	12.1	13.6	13.8
30	12.4	14.8	12.0	13.8	14.4	14.5
36	15.2	16.2	15.6	15.8	15.0	16.0
42	16.0	17.0	16.3	16.9	17.0	17.2
48	16.6	17.5	16.8	17.6	17.5	17.8
54	17.0	18.2	17.3	18.4	18.2	18.6
60	17.8	18.4	18.0	18.8	18.7	19.0
66	18.0	18.8	18.6	19.1	19.0	19.5
72			19.0	19.4	19.2	20.0

3.3 Tensile Test

Carbon contents also play a major role in the failure of the materials because higher carbon contents increases the hardness of the material which make the material stronger and more ultimate tensile strength Zhao et al, (2019). From the result obtained on the different samples of steel it could be seen that those with larger notch radius and tip radius have high elongation, proving that they are more ductile compared to smaller notch angle and tip radius.

Table 7: Tensile test for Low Carbon Steel (LCS)

	30°		45°		60°	
	0.5 mm	1.0 mm	0.5 mm	1.0 mm	0.5 mm	1.0 mm
UTS (N/mm ²)	1493.612	1630.256	1466.364	1412.888	1251.085	1675.583
Yield Strength (N/mm ²)	304.355	358.748	364.147	1280.675	1437.997	1147.443
Elongation (%)	16.144	14.793	19.652	13.355	15.411	11.986

Table 8: Tensile test for Medium Carbon Steel (MCS)

	30°		45°		60°	
UTS (N/mm ²)	1624.654	1736.189	1605.300	1365.371	1596.642	1624.144
Yield Strength (N/mm ²)	1286.736	1384.011	1363.741	1186.863	1341.587	1266.466
Elongation (%)	13.910	10.123	8.493	7.037	8.860	11.344

Steels with lower carbon content show high value of elongation and those of higher carbon content have high yield strength because of increased hardness. The failure of the component occurs at the notched point due to tensile loading, this occur because of higher stress concentration at the notched point Zhao et al, (2019); Callister and Rethwisch, (2012).

4. Conclusions

From this experiment, samples with a notch tip radius of 0.5 mm and small angles failed quicker compared to the ones having a notch tip radius of 1.0 mm and large angles. Hence the following conclusions can be drawn:

- 1. The larger the notch tip radius, the larger the absorption energy of the steel samples.
- 2. As the notch tip radius increases the sample shows more resistance to twisting.
- 3. The carbon content of the samples plays an important role on how they respond to the mechanical tests.

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