EFFECT OF NOTCH ANGLE ON FRACTURE TOUGHNESS OF AISI 4340 USING CIRCUMFERENTIALLY NOTCHED BARS

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Abstract

In this study the effect of notch angle on fracture toughness (K_{IC}) of AISI 4340 steel is investigated by using circumferentially notched bar method. The specimens have three different notch angles 45°, 60°, 75° and specimen diameters (D) - notch diameters (d) ratio (D / d) keep constant as 1.2. The purpose of the study is determining the effect of notch angle on fracture toughness. Moreover, it shows the advantages of using circumferentially notched bar specimen for fracture toughness determination of metallic materials. The obtained fracture toughness values for different notch diameter are compared with the literature. The result shows that the notch angle has significant effect on the value of fracture toughness (K_{IC}).

Keywords: Fracture, fracture toughness, fracture mechanics, circumferentially notched round bar

1. INTRODUCTION

High strength steels such as AISI 4340 is material used widely in modern aircraft structure, particularly in critical applications such as undercarriages. These steels achieve their strength at the expense of toughness, and as a result, any damage which promotes crack development and propagation increases the risk of unpredicted catastrophic failure [1]. Determination of fracture toughness is critical issue and it is based on the stress intensity factor (K_{IC}) at the crack tip. When K reaches critical value, the crack propagation becomes unstable and results failure of components [2].

Generally, K_{IC} is determined by different standardized test methods for a long time but it is possible to measure fracture toughness with using nonstandardized test methods. Notched round bar and precracked tensile specimen are common sample types. The advantages of these specimens are the plain strain condition can be obtained, because of the radial symmetry microstructure of the material along the circumferential area is uniform, specimens can be prepared easily and performing the test procedure is simple [3-6].

In the literature, the notch angle of the round bar specimen is generally 60°[4,5]. Therefore, the aim of this study is to determine the effect of notch angle on fracture toughness of AISI 4340 steels and compare the results with the literature. The specimens have three different notch angles 45°, 60°, 75° and specimen diameters (D) - notch diameters (d) ratio (D / d) keep constant as 1.2.

2. THEORETICAL BACKGROUND

K stands for the stress intensity factor at the crack tip at mode I (tensile) loading condition. When K reaches a critical value, unstable crack propagation occurs and result is failure of the component. In linear elastic fracture mechanics, the critical stress intensity factor characterizes the fracture toughness [7].

K_{IC} is calculated and formulated with using circumferentially notched bar method by different researchers.

Dieter [7] has suggested the Equation (1) for calculation of fracture toughness K_{IC} for notched bar tensile specimen of metallic materials,

$$K_{IC}=\frac{P_f}{D^{3/2}}\left[1.72\left(\frac{D}{d}\right)-1.27\right] \quad (1)$$

where P_f is the fracture load, D is the diameter of the specimen and d is the diameter of the notched section. This assumption made while formulating expression is that the specimen retains its elastic behavior until fracture occurs. This formula is valid for the D / d ratio between 1.00 and 1.25. And additional other requirement is that the length of the specimen L must be at least 4D.

According to Wang et al. [8] have given the Equation (2) for calculation of K_{IC} for notched bar specimen under tensile load,

$$K_{IC}=\frac{0.932P_f\sqrt{D}}{d^2\sqrt{\pi}} \quad (2)$$

where P_f is the fracture load, D is the diameter of the specimen and d is the diameter of the notched section. This calculation is valid for "1.2 ≤ D / d ≤ 2.1."

3. EXPERIMENTAL PROCEDURE

The chemical composition of AISI 4340 steel used in this study is given in **Table 1**. The received material came in the form of bar, approximately 30 mm in diameter.

Table 1 Chemical composition of AISI 4340 steel (wt. %)

C	Si	Mn	P	S	Cr	Mo	Ni	Fe
0.377	0.131	0.663	0.0087	0.01	1.706	0.22	1.547	Balance

The specimens without notch and with notch were prepared by using CNC lathe machine. Any heat treatment was not applied to the specimens. The specimens without notch were used to determine the mechanical properties of the received material. All of the specimens were prepared as per “DIN 50125 Testing of Metallic Materials - Tensile Test Pieces”. The notched specimens were also prepared according to DIN 50125 but additionally they had “V” type notch in the middle and notch angles (α) were 45°, 60° and 75°. For precise results, each different notch angle specimens were tested at least three times. Totally nine notched specimens were prepared for fracture toughness testing. Tensile specimen for tensile testing is shown schematically in **Figure 1** and **Figure 2** shows only the detail of the notched specimen. After the machining process, notched specimens are also shown in **Figure 3**. Definition and values of the dimensions are listed below,

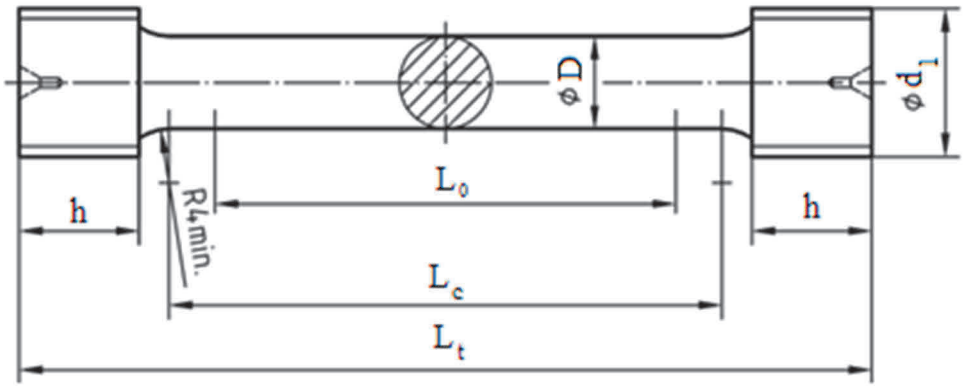

Figure 1 The schematic representation of the specimens

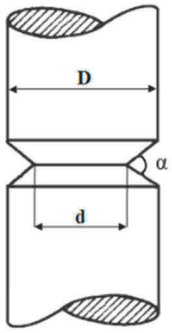

Figure 2 The details of the notched specimens

Figure 3 Notched specimens for fracture toughness testing

(D) Specimen diameter: 20 mm, (d) Notch diameter: 16.7 mm, (d_1) Diameter of ISO metric thread: M30, (h) Length of the gripped ends: 24 mm, (L_0) Original gauge length: 100 mm, (L_c) Parallel length: 120 mm, (L_t) Total length of the test pieces: 191 mm, (α) Notch angle: 45°, 60° and 75°

The tensile tests and fracture toughness tests were performed on digitally controlled servo hydraulic DARTEC tensile test machine with 400 kN capacity. All of the tests were conducted at room temperature using a crosshead speed of 4 mm/min. During the experiments, stress vs. strain curves were recorded.

The stress - strain curves of AISI 4340 steel is shown in **Figure 4**. The mechanical properties of the steel are listed in **Table 2**. Each of the results is an average value of three tensile test specimens.

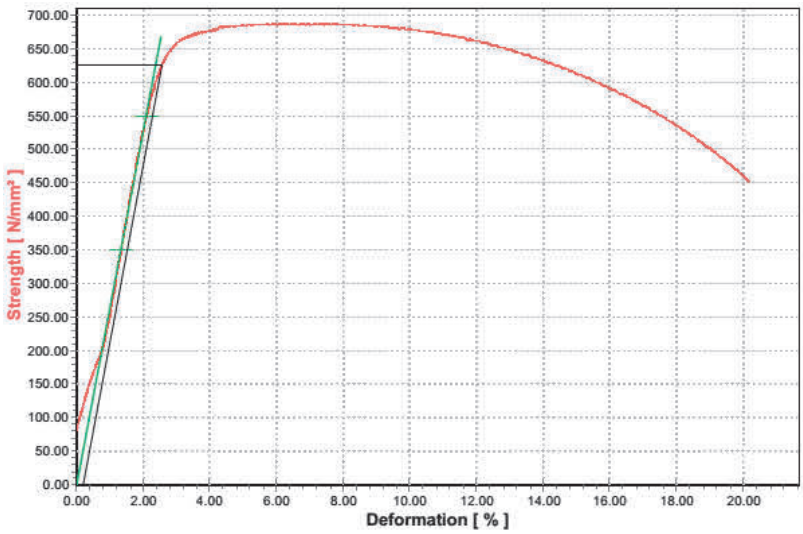

Figure 4 Stress - strain curves of AISI 4340 steel

Table 2 Mechanical Properties of AISI 4340

Ultimate Tensile Strength	Yield Strength	Elongation (%A)
687.79 MPa	625.99 MPa	20.69

After determination of the material properties of AISI 4340 steel, fracture toughness testing was performed on circumferentially notched bar specimens. Generally, researchers conducted experiments with using specimen which had notch angle of 60° in the literature [4,5]. Three notch angles (45°, 60° and 75°) were used so that the effect of angle on the mechanical properties could be observed.

Fracture loads of each circumferentially notched bar specimens were determined from stress - strain curves which were obtained from the interfaced computer software. The fracture toughness (K_{IC}) of each specimen were calculated according to Equation (1) and Equation (2) by substituting specimen diameter (D), notched section diameter (d) and fracture load (P_f). Fracture loads, fracture toughness and notch angle of the specimens are tabulated in **Table 3**.

Table 3 Ultimate Stress, Fracture Load and Fracture Toughness Data of AISI 4340 steel for Different Notch Angle

Number of Test	Notch angle α	Fracture Load kN	Fracture Toughness K_{IC} MPa$\sqrt{m}$	
			Equation 1	Equation 2
1	45°	170.21	47.53	45.38
2	45°	170.17	47.52	45.37
3	45°	169.08	47.22	45.08
4	60°	172.43	48.15	45.97
5	60°	172.47	48.16	45.98
6	60°	172.50	48.17	45.99
7	75°	177.09	49.45	47.22
8	75°	176.37	49.25	47.02
9	75°	176.47	49.28	47.05

4. RESULTS AND DISCUSSION

The relationship between the notch angle and the fracture toughness of three different notched angle specimens are demonstrated in **Figure 5** according to Equation (1) and in **Figure 6** according to Equation (2). Because of the fracture toughness values are calculated by using the fracture loads of the notched specimens, an increase in fracture loads with the increase in notch tensile strength is evident. These experimental results reveal that as notch angle increases, value of the fracture toughness increases. As the notch angle decreases, triaxiality of stresses at the notch root increases, plastic deformation is increasingly suppressed. According to obtained results, trend of fracture toughness vs. notch angle relationship is consistent with Nath and Das [2] and Bayram et al. [3] works. According to Equation (1), the mean values of fracture toughness of AISI 4340 steel are found for 45°, 60° and 75° notch angels are approximately 47.42 MPa$\sqrt{m}$, 48.16 MPa$\sqrt{m}$ and 49.32 MPa$\sqrt{m}$, respectively. According to Equation (2), the mean values of fracture toughness are found for 45°, 60° and 75° notch angels are approximately 45.27 MPa$\sqrt{m}$, 45.98 MPa$\sqrt{m}$ and 47.09 MPa$\sqrt{m}$, respectively.

The plain strain fracture toughness K_{IC} is fundamental material property that depends on many factors which are temperature, strain rate and microstructure. The magnitude of K_{IC} diminishes with increasing strain rate and decreasing temperature. Furthermore, K_{IC} normally increases with reduction in grain size as composition

and other microstructural variables are maintained constant. Several different testing techniques are used to measure K_{IC} and standardized by British Standards Institution (BSI) and American Society for Testing and Materials (ASTM). With using standardized test method, the fracture toughness of AISI 4340 steel varies from 50 MPa$\sqrt{m}$ (tempered at 260 °C) to 87.4 MPa$\sqrt{m}$ (tempered at 425 °C) in the literature [9]. The reason of higher value of K_{IC} from literature can be high ductility and toughness are obtained with heat treatment process. In this work, obtained values are in acceptable level.

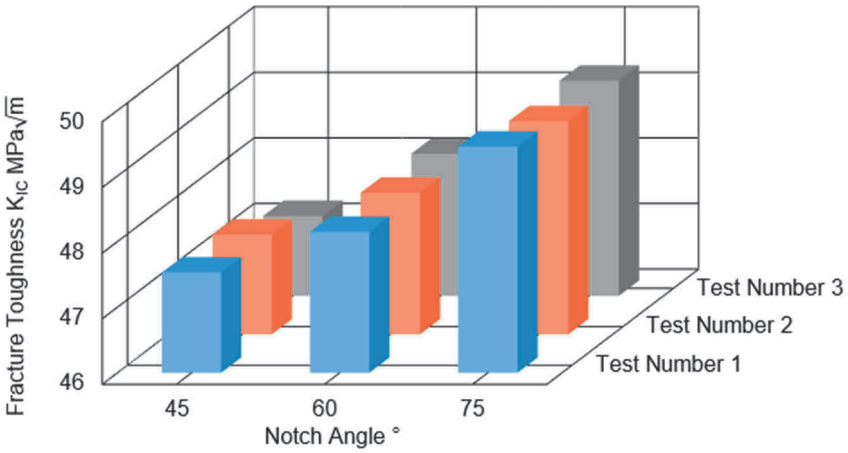

Figure 5 Notch angle vs. fracture toughness values according to Equation (1)

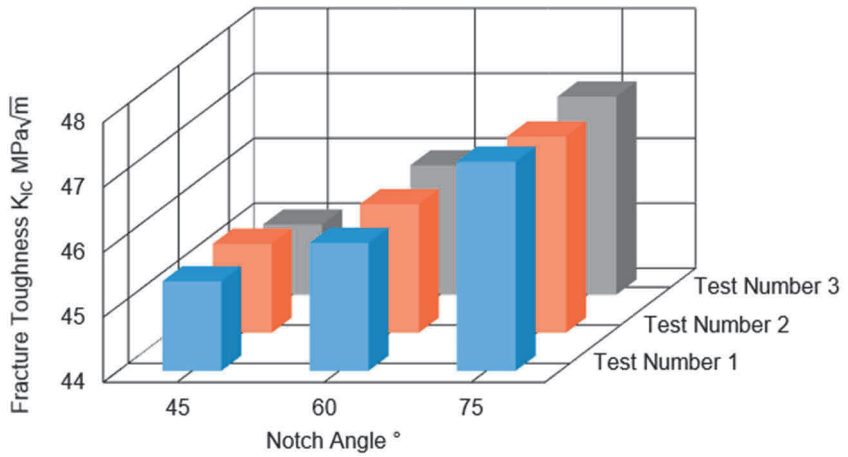

Figure 6 Notch angle vs. fracture toughness values according to Equation (2)

5. CONCLUSION

In the present study the effect of notch angle on fracture toughness (K_{IC}) of AISI 4340 steel is investigated by using circumferentially notched bar method. The following conclusions are drawn:

1) Fracture toughness of metallic materials can be determined by circumferentially notched cylindrical shape specimens.
2) This method exhibits an accurate, fast and reliable procedure for fracture toughness measurement.
3) Obtained values are found to be in good agreement with literature.
4) If notch presents in a tensile test specimen, it causes brittle fracture although the metal shows ductile mechanical properties.
5) It is observed that the value of notch angle has respectable amount effect on fracture toughness. The result indicates that as increasing notch angle, the values of the fracture toughness get increase.

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