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Case study

Failure study of a cracked speed boat steering wheel

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ABSTRACT

Failure of a cracked steering wheel is studied in this paper. Steering wheel, mounted on a speed boat, had cracks emanating from one of the fastener holes until final fracture occurred. Failure analysis, combining experimental and numerical techniques, was performed. Experimentally, fasteners torque moments were measured, visual inspection performed and material type determined (aluminum alloy AA 6061). Additionally, scanning electron microscopy examination was employed to characterize the microstructure of the fractured surface. Using finite element analysis, stress analysis of a cracked steering wheel was conducted. Stress intensities of uncracked and cracked steering wheel were compared to find out about stress concentration points. Possible causes of crack occurrence include excessive fastener torque moment, fretting between fastener and hole combined with poor machining that left marks that serve as potential crack initiation points. Obtained results are valuable for predicting fracture behavior of the cracked steering wheel and can be taken as a reference for design and exploitation process of such component.

1. Introduction

Unfavorable service conditions coupled with material imperfections and manufacturing faults can be distinguished as the cause of flaw appearance in engineering structures. Consequential crack growth can seriously affect integrity of such structures leading to threats that are particularly serious when dealing with possible fracture of components that are used in transportation vehicles.

Disastrous consequences can occur if crack growth susceptible components are used in vehicle assembly [1–3]. Using fracture mechanics principles to assess design of such components and performing adequate material selection tends to be inevitable.

One of such problems is discussed in this paper where failure analysis of a cracked steering wheel was performed. Steering wheel mounted on a speed boat was observed. Nine years of regular marine service brought two cracks emanating from one of the fastener holes on wheel. Crack propagation continued until final fracture occurred. Analysis combined experimental and numerical techniques. Prior to removing steering wheel from the boat fasteners torque moments were measured. Visual inspection followed after which material type was experimentally determined. Aluminum steering wheel was also exposed to scanning electron microscopy (SEM) examination to investigate changes in the microstructure of the

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fractured surface. All mentioned serves to determine possible causes of crack occurrence, growth and fracture. In addition, finite element (FE) analysis was used to discover stress distribution on uncracked and cracked steering wheel. Results are valuable as a reference data in the design, mounting, exploitation and for predicting fracture propagation of a steering wheel.

Previous available research on steering wheels mainly concentrates on mechanisms of force transmission [4], impact in case of collision [5] and ergonomics [6]. No previous work had been found that deals with crack occurrence or fracture of steering wheels of any kind. This paper represents a step in that direction using numerical analysis to investigate fracture behavior of cracked steering wheel and helping to improve design by finding the possible causes of crack occurrence.

2. Circumstances of the failure

Double crack occurrence was noticed on the speed boat steering wheel after about nine years of regular marine service conditions. Particular steering wheel uses an adapter to connect with steering column and it is fastened to the adapter by six fasteners. Two cracks started emanating from one of the fastener holes causing the final fracture of the wheel, Fig. 1. Four small holes are a result of clamping; a poor try of maintaining the wheel in function after the crack was noticed. General dimensions of wheel skeleton (when plastic lining removed) are also given in Fig. 1 with thickness of the central part being 5 mm. Fastener holes are numbered from 1 to 6 to identify the one with the cracks.

3. Experimental analysis

3.1. Torque value test

Prior to detaching steering wheel from the column, torque values used to tighten the fasteners were measured. Dial torque wrench was used in a common marking test where position of fastener on wheel surface was marked; fastener was loosen and retightened again until the marks were aligned and the torque required to return the fastener to its original location is taken as the original torque applied to the fastener. Measured torque values on each of the six fasteners are given in Table 1.

It can be noticed that the fastener mounted in the hole at the position 6 had relatively high torque value comparing to other five. The excessive torque value could be from initial mounting which could help in crack growth, but also a result of retightening the fastener after the cracks were noticed.

3.2. Visual examination

Detail of the crack surface can be seen in Fig. 2 where the area of fastener hole is marked. Crack propagation in both directions can be noticed.

Visual examination revealed surface marks resulting from a poor machining process along with fretting marks that came from contact of steel fastener and steering wheel. These initial damages probably served as potential crack initiation points.

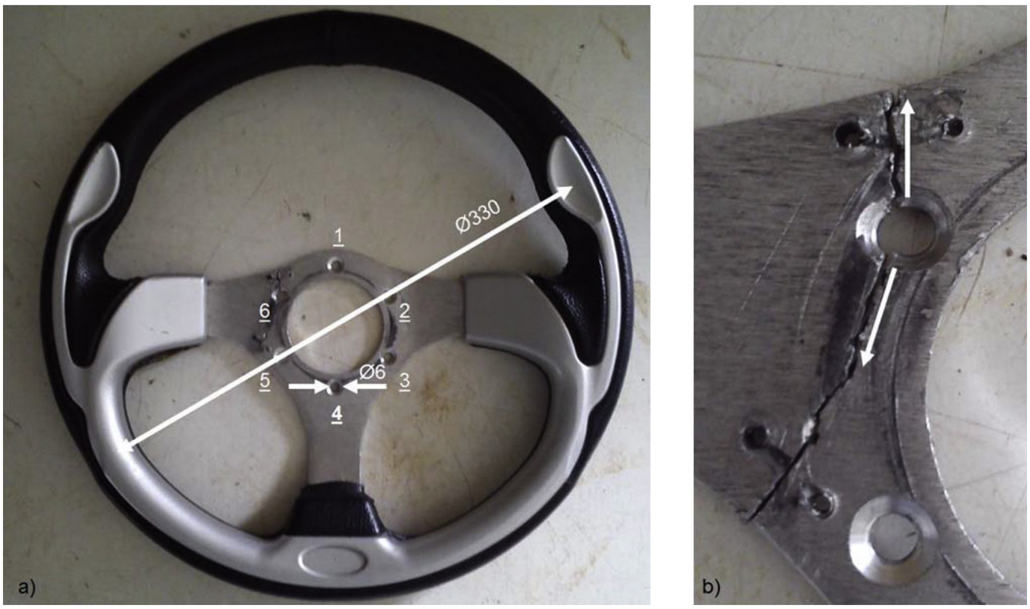


Fig. 1. (a) Cracked steering wheel with dimensions in mm. (b) Detail of the fastener hole with cracks; arrows showing direction of crack growth.

Table 1
Measured torque values on each of the six fasteners.

Fastener no.	1	2	3	4	5	6
M (Nm)	4.78	5.11	5.20	5.05	4.95	8.65

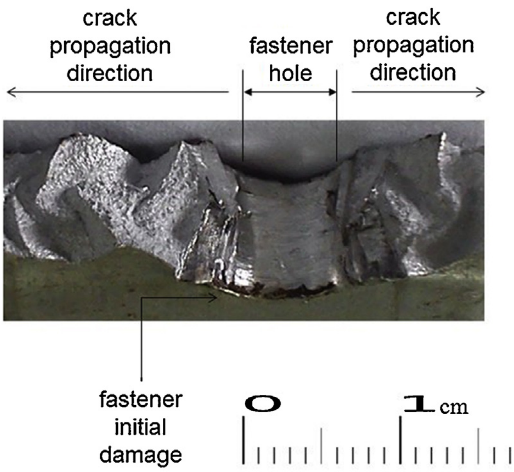


Fig. 2. Crack surface.

3.3. Material property determination

A sample of the steering wheel was given to chemical analysis to determine the type of material. Aftermarket steering wheels are usually made of aluminum or magnesium alloys and analysis discovered that the particular wheel was made of aluminum alloy AA 6061. Composition is given in Table 2 and it can be verified by analysis of the same alloy done by other authors [7].

AA 6061 is a precipitation hardening aluminum alloy with good mechanical properties and is one of the most common aluminum alloys for general purpose use. It is widely used in automotive, aero and marine industry for various applications. Since AA 6061 is not susceptible to stress corrosion cracking [8], this effect was neglected in further research.

Mechanical properties of mentioned material are given in Table 3 ($\sigma_{0.2}$ – yield strength, σ_m – ultimate tensile strength, E – elastic modulus, ε – elongation at break) and they were obtained from manufacturer's material specification [9]. Mechanical properties values indicate this is an AA 6061-O temper aluminum alloy. Annealed, this temper delivers excellent formability, but the machining represents a challenge.

3.4. Fractographic analysis

A specimen containing fracture surface was cut from the steering wheel in the vicinity of the fastener hole so it could be examined in detail using Quanta Feg 250 scanning electron microscope (SEM). Special attention was given to the surface area around fastener hole in order to notice possible crack roots.

Table 2
Chemical composition of AA 6061 [wt%].

Mg	Si	Fe	Cu	Cr	Mn	Ti	Zn	Al
0.98	0.551	0.498	0.251	0.185	0.055	0.0497	0.0256	97.937

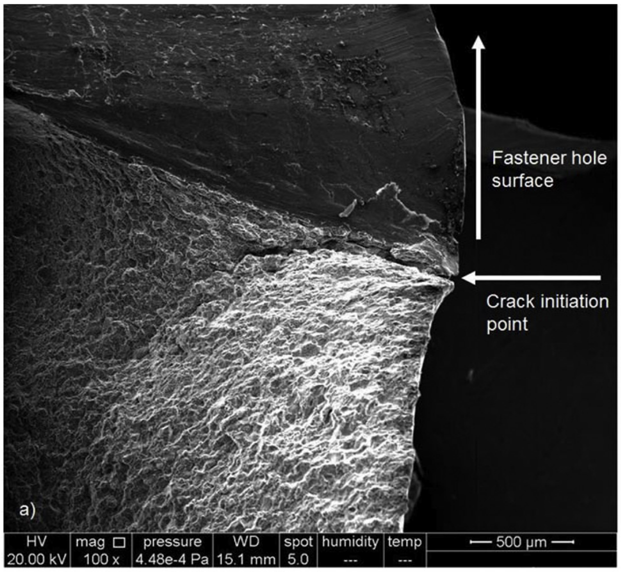
Table 3
Mechanical properties of AA 6061.

Material	$\sigma_{0.2}$ (MPa)	σ_m (MPa)	E (GPa)	ε (%)
AA 6061	55.1	124	68.9	25

Fig. 3a brings typical SEM image of fractured surface near hole opening. Crack initiation zone can be observed and it is probably caused by machining or fretting damage. Direction of crack propagation is through the thickness of steering wheel (horizontal cleavage in Fig. 3b), then toward the outer edges. Fracture area consists of dimple fracture (Fig. 3c) and transgranular cleavage, separated by crack gaps. Fracture surface can be attributed mostly as transcrystal, with scarce areas of intercrystal fracture.

4. Numerical analysis

In order to discover stress concentration points, a numerical model of cracked steering wheel was built using finite element (FE) method. Material behavior was considered linear elastic isotropic with properties set according to Table 3. Steering wheel FE model was defined according to geometry in Fig. 1, but due to symmetry only half of the wheel is modeled, Fig. 4. Symmetric boundary conditions are applied on the cross-section surface and only rotation about z-axis is allowed. First, a model without the crack was built meshed with 20-node isoparametric brick elements. After that, model with two full-through cracks emanating from the fastener hole no. 6 was built with several different crack lengths incorporated ($a/R = 0.25, 0.5, 0.75, 1, \ldots, 3$; with a being crack length, and R fastener hole radius). To accommodate the singular stress field in the vicinity of the crack tips, these areas were meshed with 20-node isoparametric brick elements collapsed to wedges. Particular care was taken when meshing area around the crack tips ensuring mesh fine enough to properly capture stresses and deformations. Mid-side nodes of the elements were moved to 1/4-point positions toward the crack tip in order to achieve strain/stress singularity at the corner of a 20-node isoparametric element [10]. This can be later used to estimate stress intensity factor, an important fracture mechanics parameter that completely defines crack tip



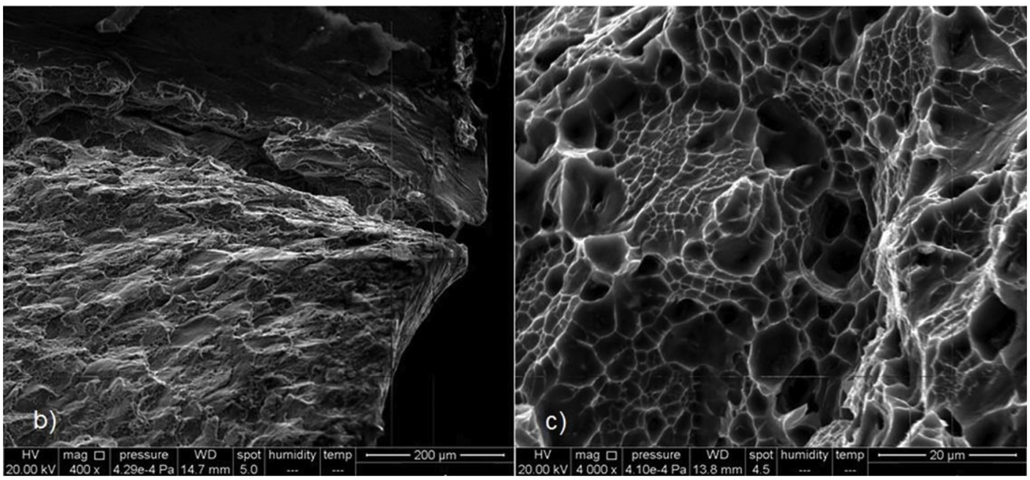


Fig. 3. (a) Crack surface. (b) Magnified crack surface. (c) Spherical dimples.

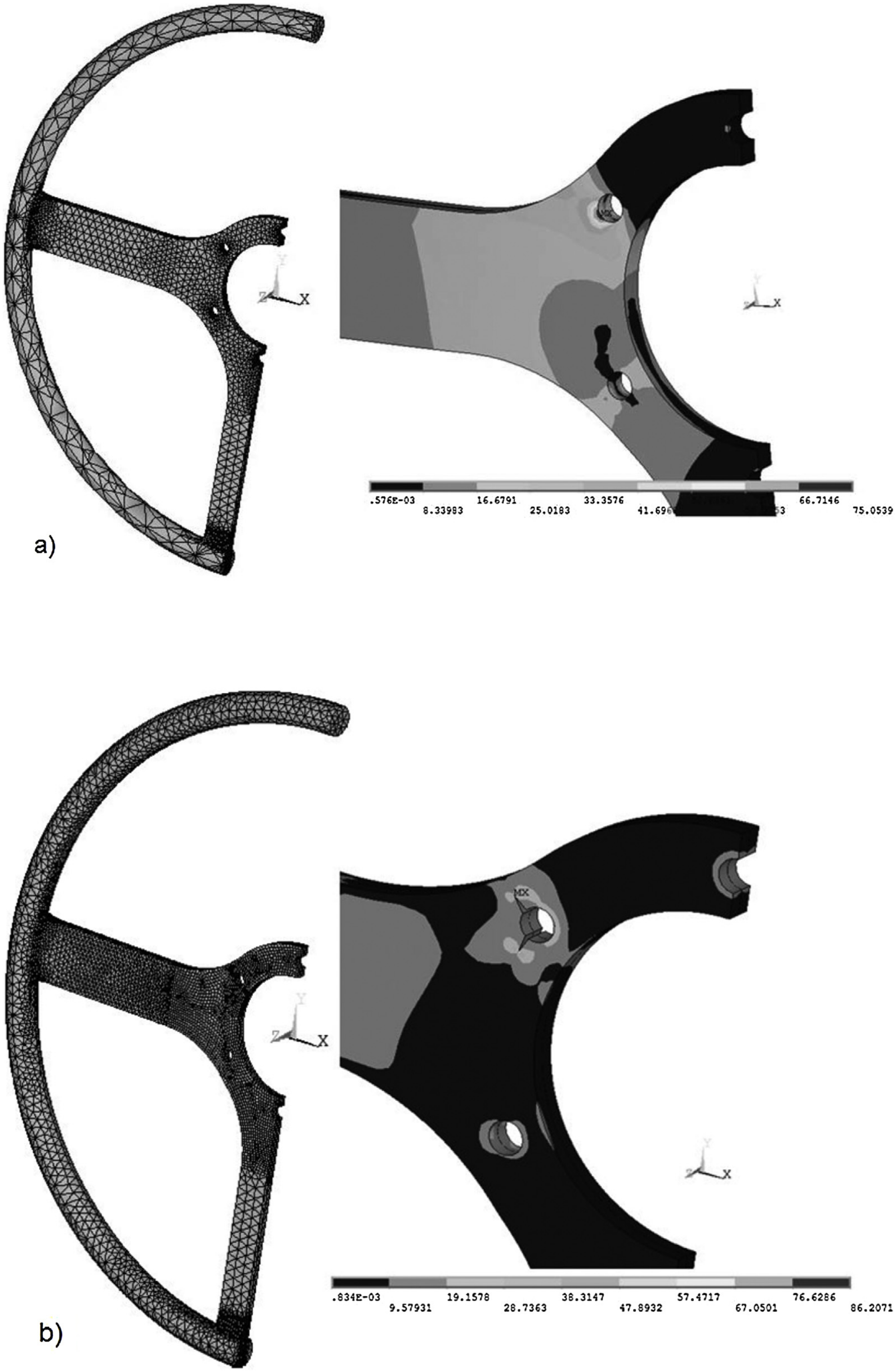


Fig. 4. Von Mises stress distribution on FE model of steering wheel. (a) Without cracks. (b) With cracks.

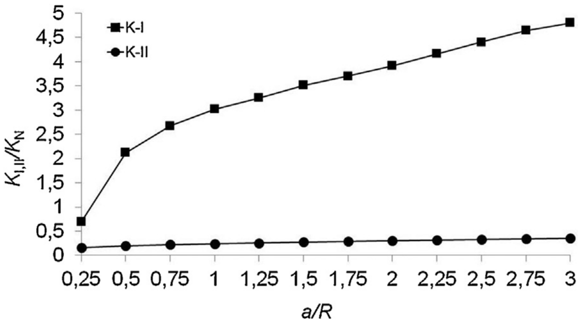


Fig. 5. Calculated normalized mode I and II stress intensity factors.

conditions, i.e. stress, strain and displacement values and it is used to assess fracture behavior for materials that exhibit small-scale yielding at the crack tip.

Contact was defined between hole surface and fastener. As for load, fastener holes are loaded according to torque loads measured in Table 1. The fastener surface is assumed to be smooth. Thus, it transmits only radial loads to the hole. Additionally, load of driver's arm resting on steering wheel is added to juncture of rim and horizontal spoke with a value of 40 N [11].

Fig. 4 shows Von Mises stress levels on FE model with and without cracks. Observing the example without cracks, maximum stress level can clearly be seen on the outer edge of fastener hole no. 6 with level of about 75 MPa. With two cracks incorporated into the model, stress level rises and shifts from hole to crack tip following the propagation of the crack tip, in accordance with the fracture mechanics principles.

Using numerical analysis, mode I and II stress intensity factors (SIF) are calculated for an array of different crack lengths a relative to fastener hole radius R (a/R = 0.25, 0.5, 0.75, 1, . . ., 3). Values of SIFs are normalized according to relation:

$$K_N = p\sqrt{\pi a}, \tag{1}$$

where p is internal pressure in the hole resulting from tightened fastener.

Results are given in Fig. 5. It can be noted that mode I SIFs dominate over mode II values. Also, there is a considerable growth of SIF with the crack changing length between a/R = 0.25 and 0.5; after that SIF values grow steadily.

5. Results and discussion

Experimental study of fractured speed boat steering wheel revealed the material to be aluminum alloy AA6061-O, one of the most common aluminum alloys, widely used in marine industry, among others.

Visual examination of cracked steering wheel revealed machining and fretting marks on the surface of fastener hole from which cracks emanated. These marks served as initiation points for crack growth.

Measured torque values of fasteners showed that the fastener at hole from which cracks emanated had relatively high torque value comparing to others. This excessive load, combined with the load of driver's hand, speeded up crack propagation.

Detailed SEM examination of the fractured surface confirmed cracks growing from the mentioned marks and showed direction of crack propagation to be through the thickness of steering wheel and toward the outer edges. Fracture area consists of dimple fracture and transgranular cleavage separated by crack gaps in the vicinity of the fastener hole. Surface consists of some cleavage step pattern that reminds of Wallner lines. Cracks between flat surfaces and cleavage suggest possible fracture initiation point.

In addition, numerical analysis showed maximum stress level at the point of crack initiation on the outer edge of fastener hole. Same load produced higher stress level when the cracks were added to the FE model shifting them to the crack tips making way for propagation of the cracks. Joint stresses produced in the local stress concentration point at the fastener holes further enhance the fracture evolution.

6. Conclusion

Fracture behavior of a cracked speed boat steering wheel has been studied in this paper. During regular use cracks started emanating from one of the six fracture holes by which the wheel was attached to column. After final fracture, wheel was detached from boat and subjected to fracture analysis. Results, obtained by experimental and numerical approach, suggest greater care should be taken in machining and mounting the wheel in order to avoid initial damage to the surface that could serve as a point of crack initiation. Also, care should be taken when tightening the fasteners not to exceed the torque limits as the additional load can improve crack growth. This study gives insight into the fracture behavior of a cracked steering wheel and can be found useful in the design process, mounting or exploitation of such component.

Acknowledgment

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