УДК 539.432

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NOTCH EFFECT ON CYCLIC DEFORMATION OF STRUCTURAL STEEL UNDER AXIAL AND TORSIONAL LOADING

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ВЛИЯНИЕ КОНЦЕНТРАЦИИ НАПРЯЖЕНИЙ НА ЦИКЛИЧЕСКОЕ ДЕФОРМИРОВАНИЕ СТАЛИ 20 ПРИ РАСТЯЖЕНИИ И КРУЧЕНИИ

Notch effects on uniaxial and torsion fatigue behavior of low-carbon steel 20 are investigated in this study. Constant amplitude axial and torsion both load and strain-controlled tests were conducted on smooth and notched tubular specimens. Maximum principal stress theory was chosen as driving parameter for experimental program. Torsion loading resulted in significantly shorter lives and fatigue data could not be correlated by the maximum principal stress theory for smooth specimens. However, considering fatigue notch factor for notched tubes the maximum principal stress theory gives acceptable results. The Finite Element Analysis was used to estimate local stress-strain response at the notch root due to stress concentration. Fatigue strength of notched specimens was predicted based on fatigue strength of the smooth specimens and the fatigue notch factor. As compared to the notched specimens fatigue data the predicted lives are slightly conservative for axial loading and overly conservative for torsion loading.The Fatemi-Socie (FS) critical plane parameter was found to correlate all constant amplitude data of both specimen geometries well since this shear-based critical plane damage parameter represents the actual shear damage crack initiation mechanism experimentally observed for both smooth and notched specimens and under both axial and torsion loadings.
Keywords: Notch deformation, Notch strain, Notch stress, Life Prediction, Low carbon steel

Introduction

The most common cause for fatigue crack initiation in structural components is at stress concentrators such as notches. Grooves and keyholes on shaft, holes, fillets, thread, and welded joints are all notches. Even nominal elastic behavior may effects in exciding of yield limit around the notch.

Service loading of some notched engineering components such as pipes, shafts, springs, curved shells is often multiaxial. In addition to the multiaxial case, many structures are also under variable amplitude or periodic overloading conditions. In comparison with axial loading, torsional and multiaxial fatigue studies are relatively limited.

The notch effect on multiaxial fatigue behavior has been evaluated by some researches. Atzori at al. [1] conducted a multiaxial fatigue experimental study on V-notched specimens. Their experiments included two nominal load ratios, and 0, while keeping constant and equal to the unity the biaxiality ratio $\lambda = \sigma_a / \tau_a$. They found that multi-axial fatigue strength is significantly affected by the nominal load ratio, whereas the influence of the load phase angle seems to be negligible. Almost 10 times reduction in life was observed when the load ratio changes from $R = -1$ to 0. Yi-Ming and Wei-Wei [2] investigated crack initiation life for solid cylinders with transverse circular holes made from AISI 316 stainless steel under in-phase and out-of-phase multiaxial loading. The crack initiation life of notched specimens under out-of-phase multiaxial loading is shorter that that under in-phase multiaxial loading due to additional cyclic hardening effect. The shortest life was obtained for 90^o out-of-phase path. Gao at al. [3] studied fatigue behavior of V-notched shafts made of 16MnR steel with sharp and blunt notch radii. They showed that significant notch size effect on the fatigue life under different loading paths and notch effect is more significant for higher loading cycle fatigue. Fatigue analysis was conducted by employing two critical plane multiaxial fatigue criteria, especially Jiang criterion and Fatemi-Socie model. Results suggest that fatigue life predictions based on the two fatigue criteria and the local stress and strain obtained from the FE method are in excellent agreement with the experimental observations. Sun at al. [4] conducted strain-controlled fatigue tests for GH4169 superalloy thin tubular and V-notched specimens under in-phase and two different out-of-phase loading paths at 650^oC. As can be found from experimental results for notched specimens, all of 90^o out-of-phase fatigue lives are longer in comparison with in-phase data. This effect may be also explained by sufficient additional hardening for this material at the root of the notch due to high plastic deformation. As a result, a fatigue damage parameter was proposed to predict the fatigue crack initiation life for notched specimen. Alfredsson at al. [5] studied notch effects on multiaxial fatigue behavior for a bainitic high strength roller steel. Thin-walled specimens with two the same small two opposite holes with seven different diameters in range of 1.0 to 2.6 mm, were subjected to different non-proportional load cycles. The outer and inner diameters were 16 mm and 14.4 mm respectively. It is not possible to estimate notch size effect as well as load non-proportionality effect on fatigue behavior due to limited number of tests. However, both the Findley criterion and the Haigh diagram could predict the crack position at the hole. The Findley criterion did however give a more clear indication of the expected crack position.

In addition, many engineering notched structures are also subjected to different combination of cyclic and static loadings [6-8]. These results show that the addition of static compression to torsion cycling gives longer lifetime and static tension – shorter fatigue life in comparison with pure torsion cycling due to notch-weakening.

In this paper, first the experimental program including the material, specimen fabrication, strain paths employed, and experimental procedure used are reviewed. Next, experimental results and analysis details are presented, followed by a discussion of experimental observations. Then, correlation of predicted and observed fatigue life of axial and torsion loadings are presented. Finally, conclusions from the experimental observations and analyses conducted are presented.

Material and experimental procedure

Low-carbon steel 20 was used at this study. The chemical composition of the material is as follows (mass%): C 0.24, Si 0.25, Mn 0.45, Cr 0.2. One basic geometry for two different types of specimens shown in Figure 1 with 1.1 mm wall thickness, 22 mm inside diameter, and 40 mm gauge length was used in this work. One type was a tubular smooth thin-walled specimens, the other type was the same thin-walled specimen with 3.4 mm circular through-thickness hole at the middle of gauge length.

Load and strain controlled fatigue tests were carried out at room temperature using servohydraulic machine with independent control of push-pull and torsion loads with frequency of 0.5-3 Hz.

Fully-reversed sinusoidal axial and torsion waveforms were applied for load/strain controlled constant amplitude tests. Strain control tests were carried out on smooth specimens only under uniaxial loading. Load control regime corresponds to testing of all notched specimens and smooth specimens under torsion. In order to make sure in data correlation between load and strain control tests, two different load control level for smooth specimens were chosen for uniaxial case.

The 5% load drop for uniaxial strain control tests and 5% strain and rotation angle increment for uniaxial and torsion load control tests respectively, as compared to midlife stable cycle for smooth specimens were considered as a small crack initiation life. For load control tests of notched specimens small crack initiation life was assumed with three different cases, especially estimated based on stress threshold, 0.5 mm and 1.0 mm. The K–T diagram was proposed to describe the relationship between the stress threshold and the crack length by Katagawa and Takahashi. For the short crack at notch under the axial cyclic loading, the stress intensity factor range may be expressed as [9]

$$\Delta K_{th} = Ff\,\frac{K_t \Delta\sigma_e}{2\cdot K_f}\left[\left(1+2\frac{a}{r}\right)^{-1/2}+\left(1+2\frac{a}{r}\right)^{-3/2}\right]\sqrt{\pi a} \tag{1}$$

where a is the crack length from the notch root, $r = 1.7$ mm is the notch root radius and f is correction coefficient which takes 1 if $a/r < 0.2$ which determines the maximum value of the contact stress at the crack tip. The stress concentration factor K_t was found by using Fatigue on-line software referring Peterson's plot. The fatigue notch factor K_f may be obtained from Neuber equation [10]:

$$K_f = 1+\frac{K_t - 1}{1+\sqrt{\rho/r}}$$

where the material characteristic length, ρ, is 0.185 mm. A shape factor F takes 1.05 [11]. Fatigue limit range $\Delta\sigma_e =$ 384 MPa and fatigue threshold stress intensity factor range $\Delta K_{th} = 9MPa\sqrt{m}$ were found from experimental results. Substation of these values to Equation (1) gives solution for crack initiation size based of stress threshold of notched specimens equal to 0.2 mm.

Experimental Results and Analysis

Axial strain amplitudes, $\Delta\varepsilon/2$ and axial stress amplitude, $\Delta\sigma/2$ were the controlling parameters for smooth specimens under strain control and load control tests respectively. Axial strain amplitude was measured directly from the extensometer output. Axial stress amplitude was considered uniform throughout the cross section.

The only axial and shear stress amplitude, $\Delta\sigma/2$ and $\Delta\tau/2$ were the controlling parameters for all notched specimens. The axial nominal stress was calculated by dividing the axial load by the gross cross-section area. Shear stress amplitude, τ_a, which exceeding yield strength was calculated from:

$$\tau_a = \frac{\Delta\tau}{2} = \frac{\Delta T}{2 r_m A}$$

where $\Delta T/2$ is torque amplitude, A is specimen gross cross section area, and r_m is mid radius. In case of fully elastic loading, shear stress was calculated by considering polar moment of inertia. Axial and shear applied strain and stress amplitudes as well as cycles to failure, N_f for each constant amplitude fatigue test of low-carbon steel 20 are listed in Tables 1.

Table 1

Constant amplitude axial and torsion fatigue tests of smooth and notched specimens

Control mode	$\frac{\Delta\varepsilon}{2}$	$\frac{\Delta\sigma}{2}$ MPa	$\frac{\Delta\tau}{2}$ MPa	σ_{a1} MPa	$\bar{\sigma}_a$ MPa	$\sigma_{n,\max}$ MPa	N_f Cycles
Smooth specimens							
Axial	0.0100	411	-	411	411	206	50
Axial	0.0070	350	-	350	350	175	135
Axial	0.0030	277	-	277	277	139	3,400
Axial	0.0020	261	-	261	261	131	13,120
Axial	0.0015	232	-	232	232	116	51,500
Axial	0.0010	192	-	192	192	96	>972,000
Axial	0.0031	300	-	300	300	150	2,050
Axial	0.0016	230	-	230	230	115	151,000
Torsion		-	190	190	329	0	8,573
Torsion		-	175	175	303	0	45,810
Torsion		-	149	149	258	0	242,000
Notched specimens							
Axial		269	-	269	269	135	315
Axial		250	-	250	250	125	495
Axial		200	-	200	200	100	2,115
Axial		144	-	144	144	72	20,900
Axial		106	-	106	106	53	140,500
Torsion		-	149	149	258	0	5,407
Torsion			149	149	258	0	5,910
Torsion		-	121	121	209	0	34,700
Torsion		-	87	87	151	0	120,000
Torsion		-	87	87	151	0	276,000
Torsion		-	65	65	113	0	>1,150,000

From Peterson's plot, the tensile and shear stress concentrator factors are 3.29 and 3.98, respectively. Fatigue behavior of notched components depends on not only elastic stress concentrator factor. Materials strength is considered by fatigue notch factor, K_f. From [11], the fatigue notch factor takes 2.73 and 3.21 for axial and torsion loading, respectively.

Fatigue strength of notched component could be predicted as strength of smooth component divided by analytical factor. To apply S-N approach, axial K_{fA} and shear K_{fT} fatigue notch factors are used in this study. For fatigue life of 10^6 cycles it was estimated fatigue strength of notched specimens as S_A / K_{fA} and S_T / K_{fT}, where S_A and S_T are axial and torsion fatigue strength of smooth specimens.

The von Mises was used to correlate axial and torsion fatigue life of notched specimens by using of S-N approach in following from

$$\bar{\sigma}_a = \sqrt{3}\left(K_{fT} \cdot S_{aT}\right)$$

where S_{aA} and S_{aT} are amplitudes of nominal axial and shear stresses. A correlation of fatigue data for studied steel is presented in Fig. 1. As can be seen from the Figure, ten times overestimation in fatigue life was found for S-N approach due to conservative methodology.

The following shear form of the Fatemi-Socie critical plane parameter was also used to correlate constant amplitude fatigue data

$$\frac{\Delta\gamma_{\max}}{2}\left(1 + k\frac{\sigma_{n,\max}}{\sigma_y}\right) = \left[(1+\nu_e)\frac{\sigma'_f}{E}(2N_f)^b + (1+\nu_p)\varepsilon'_f(2N_f)^c\right] \cdot \left[1 + k\left(\frac{\sigma'_f}{2\sigma_y}(2N_f)^b\right)\right]$$

where $\nu_e = 0.3$ and $\nu_p = 0.5$, are elastic and plastic Poisson's ratios. $k = 1.0$ was assumed for studied steel. The shear strain-life curve was generated based on von Mises criterion. The FS parameter was associated with local stress-strain condition based on FE analysis results. Correlation of constant amplitude data by the FS parameter is presented in Fig.2.

As can be seen from these Figures, FS parameter fits the experimental data both for smooth and notched specimens very well. Based on FE analysis, the critical shear planes locate at the notch root on 0°, ±180° under axial loading and ±45°, ±135° for torsion loading. The same locations were found from experimental results. In addition, the fracture surfaces for both cases of loading associated with maximum shear plane. It explains FS parameter ability to predict fatigue life very well.

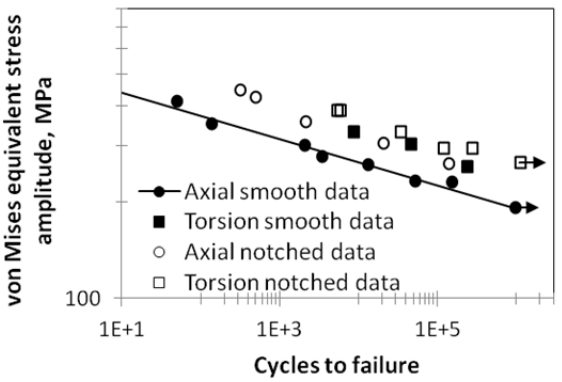

Fig. 1. Correlation of axial and torsion data by using of von Mises equivalent stress

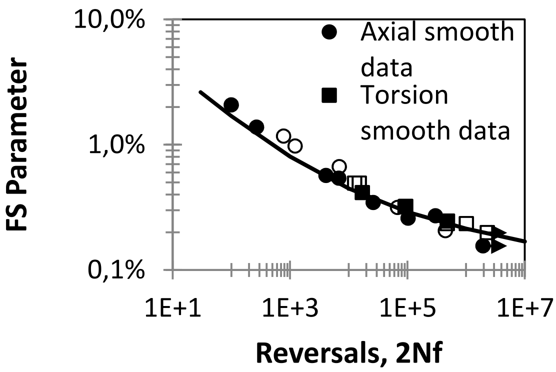

Fig. 2. Correlation of axial and torsion data by usingF-S parameter

Conclusion

Although maximum principal stress criterion could correlate axial and torsion constant amplitude data of notched specimens with a factor of 4, it could not correlate axial with torsion data of smooth specimens. The shear fracture mechanism was observed for low-carbon steel 20 under axial and torsion loading based of fracture surface orientation and FE analysis simulation. The Fatemi-Socie parameter was found to correlate both smooth and notched data very well.

Анотація. *В роботі досліджується вплив концентрації напружень на втомну поведінку сталі 20 при осьовому навантаженні та випробуваннях на кручення. Експериментальні дослідження проведено на трубчастих зразках з отвором та без концентратору при одновісному розтяганні-стисканні та знакозмінному крученні. Критерій максимальних нормальних напружень було використано в якості контролюючого параметру програми випробувань. Експерименти при крученні зразків без концентраторів продемонстрували занижені результати на втому, які не можуть бути описані за допомогою теорії максимальних нормальних напружень. Однак, з урахуванням втомного коефіцієнту концентрації теорія максимальних нормальних напружень дає задовільні результати для зразків з отвором. Для оцінки напружено-деформованого стану поблизу концентратора було використано скінченно-елементний аналіз. Втомна міцність зразків з концентратором розраховувалась на основі даних на довговічність для гладких зразків та значень втомного коефіцієнту концентрації напружень. Прогнозовані значення довговічності для зразків з концентратором напружень виявилися консервативними, при цьому для одновісного навантаження у меншій мірі в порівнянні з результатами для кручення. Встановлено, що прогнозування довговічності може бути успішно виконане згідно критерію Фатемі-Сосі. Цей критерій заснований на пошкоджуваності матеріалу по зсувному типу, що відображує реальний механізм зародження тріщини, спостерігаємий у експериментах як для гладких зразків так і для зразків з концентратором при навантаженні осьовою силою та крутним моментом.*

Аннотация. *В данной работе исследуется влияние концентрации напряжений на усталостную долговечность стали 20 при осевом нагружении и испытаниях на кручение. Экспериментальные исследования проводились на трубчатых образцах с отверстием и без него при одноосном растяжении-сжатии и знакопеременном кручении. Критерий максимальных нормальных напряжений был использован в качестве контролируемого параметра программы испытаний. Эксперименты при кручении образцов без концентраторов продемонстрировали заниженные результаты по долговечности, которые не могут быть описаны с помощью теории максимальных нормальных напряжений. Однако, с учетом усталостного коэффициента концентрации теория максимальных нормальных напряжений дает удовлетворительные результаты для образцов с отверстием. Для оценки напряженно-деформированного состояния вблизи концентратора был использован, конечно-элементный, анализ. Усталостная прочность образцов с концентратором рассчитывалась на основании данных по долговечности для гладких образцов и значений усталостного коэффициента концентрации напряжений. Прогнозируемые значения долговечности для образцов с концентратором напряжений оказались консервативными, при чем для одноосного нагружения в меньшей мере по сравнению с результатами для кручения. Установлено, что прогнозирование долговечности может быть успешно выполнено согласно критерия Фатеми-Соси. Этот критерий основан на повреждаемости материала по сдвиговому типу, что отображает реальный механизм зарождения трещины,*

наблюдаемый в экспериментах, как для гладких образцов, так и для образцов с концентратором при нагружении осевой силой и крутящим моментом..

1. *Atzori B.* Multi-axial fatigue behavior of a severely notched carbon steel. / *Atzori B, Berto F, Lazzarin P, Quaresimin M.* // - Int J Fatigue. -2006; - № 28: - С. 485-493.
2. *Jen YM,* Crack initiation life prediction for solid cylinders with transverse circular hole under in-phase and out-of-phase multiaxial loading. / *Jen YM, Wang WW* // - Int J Fatigue. -2005; - № 27: - С. 527-539.
3. *Gao Z.* An investigation of fatigue of a notched member. / *Gao Z, Qui B, Wang X, Jiang Y* // - Int J Fatigue. -2010; - № 32: - С. 1960-1969.
4. *Sun GQ.* Prediction of fatigue lifetime under multiaxial cyclic loading using finite element analysis. / *Sun GQ, Shang DG* // - Materials and Design. - 2010; - № 31: - С. 126–33.
5. *Alfredsson B.* Fatigue crack initiation an growth at holes in a high strength bianitic roller bearing steel when loaded with non-proportional shear and compressive cycles. / *Alfredsson B, Watz V, Olsson E.* // - Int J Fatigue. - 2011; - № 33: - С. 1244-1256.
6. *Tipton SM.* Advances in multiaxial fatigue life prediction for components with stress concentrations. / *Tipton SM, NelsonDV.* // - Int J Fatigue. -1997; - № 19; - С. 503-515.
7. *Thomson KD.* Fatigue crack growth in notched and plain shafts subjected to torsion and axial loading. / *Thomson KD, Sheppard SD.* // - Engng Fract Mechanics. -1992; - № 43(1): - С. 55-71.
8. *Ohkawa C.* Notch effect on torsional fatigue of austenitic stainless steel: Comparison with low carbon steel. / *Ohkawa C, Ohkawa I.* // - Engng Fract Mechanics. - 2011; - № 78: - С. 1577-1589.
9. *Kujawski D.* Estimations of stress intensity factors for small cracks at notches. // - Fat. Fract. Engng. Mater. Struct. - 1991; - № 14: - С. 953-965.
10. *Neuber H.* Kerbspannungstehre, Springer, Berlin, 1958; Translation Theory of Notch Stress, U.S. Office of Technical Services, Washington, DC, 1961.
11. *Fuhring H.,* Approximation functions for K-factors of cracks in notches. // - Int J Fracture. - 1973; - № 9: - С. 328-331.

REFERENCES

1. *Atzori B,* Berto F, Lazzarin P, Quaresimin M. Multi-axial fatigue behavior of a severely notched carbon steel. Int J Fatigue 2006; no 28: pp. 485-93.
2. *Jen YM,* Wang WW. Crack initiation life prediction for solid cylinders with transverse circular hole under in-phase and out-of-phase multiaxial loading. Int J Fatigue 2005; no 27: pp. 527-39.
3. *Gao Z,* Qui B, Wang X, Jiang Y. An investigation of fatigue of a notched member. Int J Fatigue 2010; no 32: pp. 1960-9.
4. *Sun GQ,* Shang DG. Prediction of fatigue lifetime under multiaxial cyclic loading using finite element analysis. Materials and Design 2010; no 31: pp. 126–33.
5. *Alfredsson B,* Watz V, Olsson E. Fatigue crack initiation an growth at holes in a high strength bianitic roller bearing steel when loaded with non-proportional shear and compressive cycles. Int J Fatigue 2011; no 33: pp. 1244-56.
6. *Tipton SM,* Nelson DV. Advances in multiaxial fatigue life prediction for components with stress concentrations. Int J Fatigue 1997; no 19; pp. 503-15.
7. *Thomson KD,* Sheppard SD. Fatigue crack growth in notched and plain shafts subjected to torsion and axial loading. Engng Fract Mechanics 1992; no 43(1): pp. 55-71.
8. *Ohkawa C,* Ohkawa I. Notch effect on torsional fatigue of austenitic stainless steel: Comparison with low carbon steel. Engng Fract Mechanics 2011; no 78: pp. 1577-89.
9. *Kujawski D.* Estimations of stress intensity factors for small cracks at notches. Fat. Fract. Engng. Mater. Struct. 1991; no 14: pp. 953-65.
10. *Neuber H.* Kerbspannungstehre, Springer, Berlin, 1958; Translation Theory of Notch Stress, U.S. Office of Technical Services, Washington, DC, 1961.
11. *Fuhring H.,* Approximation functions for K-factors of cracks in notches. Int J Fracture1973; no 9: pp. 328-31.