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Crack initiation and propagation in torsional fatigue of circumferentially notched steel bars

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ABSTRACT

Circumferentially notched bars of austenitic stainless steel, SUS316L, and carbon steel, SGV410, with three different notch-tip radii were fatigued under cyclic torsion without and with static tension. The torsional fatigue life of SUS316L was found to increase with increasing stress concentration under the same nominal shear stress amplitude. Electrical potential monitoring revealed that the crack initiation life decreased with increasing stress concentration, while the crack propagation life increased. This anomalous notch-strengthening effect was ascribed to the larger retardation of fatigue crack propagation by sliding contacts of fracture surfaces. The superposition of static tension on cyclic torsion causes notch weakening. The notch-strengthening effect in torsional fatigue was not found in carbon steels, SGV410. The difference in the crack path of small cracks near notch root between stainless steel and carbon steel gives rise to the difference in the notch effect in torsional fatigue. The factory-roof shape observed on fracture surfaces of SUS316L became finer with higher stress amplitude and for sharper notches. The superposition of static tension makes the factory-roof shape less evident. Under higher stresses, the fracture surface was smeared to be flat. The fracture surfaces of SGV410 became smoother with increasing stress amplitude and notch acuity. The three-dimensional feature of fracture surfaces clearly showed the difference of the topography of fracture surfaces. The topographic feature was closely related to the amount of retardation of crack propagation due to the sliding contact of fracture surfaces.

1. Introduction

Fatigue fracture of several engineering components such as transmission shafts, pipes and springs occurs under combined torsional and axial loading. Notches or stress concentrations are the common site of crack initiation and usually weaken the fatigue strength of components. The assessment of the notch weakening effect on the fatigue strength and life is essential in fatigue designs. In conventional designs, the notch strength reduction factor, K_f, which is defined as the ratio of the fatigue strength of smooth specimens to that of notched specimens, has been used to evaluate the reduction of the fatigue strength. It is well known that the K_f value is higher than one and lower than the elastic stress concentration factor, K_t. The difference between K_f and K_t comes from several factors such as stress gradient, structural size, material volume and plasticity effect [1].

An anomalous phenomenon of the notch-strengthening effect was found in torsional fatigue of circumferentially notched bars of austenitic stainless steels [2–4]. The fatigue life of notched bars was found to be longer than that of smooth bars, and to increase with increasing stress concentration factor under the same amplitude of the nominal shear stress. This anomalous notch-strengthening was also found in NiCrMo hardened and tempered steel [5], pure titanium [6], but not found in carbon steels [4,7,8].

In torsional fatigue of circumferentially notched bars, a factory-roof type fracture surfaces are formed under low stress cycling and the sliding contact of fracture surfaces causes the retardation of crack propagation [9–13]. At high stress cycling, flat fracture surfaces are formed and the crack retardation due to sliding contact is less pronounced. Superposed static tension also reduces the crack surface contact [12]. The crack extension was monitored by the dc electrical potential method by assuming concentric cracks propagating toward the center of bars [12,14]. Cracks formed near notches decelerate and then stop at low stress amplitudes [13]. Non-propagating cracks are usually found near notches in unbroken specimens fatigued at the fatigue limit [5,7,13]. For torsional fatigue, it is necessary to distinguish between different thresholds for crack initiation and propagation [5,7,15]. Yu and others proposed the resistance-curve method to predict the crack initiation and propagation thresholds [13]. The crack propagation path is three-dimensionally complexly shaped. To estimate the reduction of the stress intensity due to the sliding contact of the fracture surfaces, Vaziri and Nayeb-Hashemi [16] modeled a crack formed

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from a circumferential notch to be flat and propagate concentrically toward the center. They calculated the shielding stress intensity factor from the friction stress obtained by the pressure distribution on the facture surface and the friction coefficient. The amount of shielding is very much dependent of the asperity shape of factory-roof type fracture surfaces [17].

In the present paper, circumferentially notched bars of austenitic stainless steel and carbon steel with three different notch-tip radii were fatigued under cyclic torsion without and with static tension. The dc electrical potential method was used to monitor continuously the initiation and propagation behavior of small cracks from notches. The difference in the notch effect on crack propagation behavior between stainless steel and carbon steel is discussed on the basis of the crack path morphology and fracture surface topography observed by scanning electron microscopy (SEM).

2. Experimental procedure

2.1. Materials and specimens

The material used is austenitic stainless steel (JIS SUS316L) and carbon steel (JIS SGV410) for structural use in nuclear power plants [2,3,8]. The specimen of SUS316L was machined from solution-treated hot-rolled bars, and those of SGV410 was machined from the central region of hot-rolled plates with 40 mm thickness. The axial direction of the specimens was parallel to the rolling direction. The yield strength and tensile strength of SUS316L were 260 and 591 MPa, and those of SGV410 were 275 and 470 MPa. The diameter of the gage section of smooth specimens is 16 mm (named SM-M specimen) or 10.5 mm (SM specimen), and the length is 40 mm. Fig. 1 shows the shapes of notched specimens which have circumferential notches with three different root radii. The specimens with the radii 4.5, 1.07, and 0.22 mm are named NA, NB, and NC specimens, respectively. All the specimens were finished by buffing using diamond past. The elastic stress concentration factor for the shear stress under torsion for NA, NB, and NC specimens calculated by the finite element method (FEM) was 1.17, 1.55, and 2.54, and that for the tensile stress was 1.50, 2.50, and 5.07, respectively. Moreover, specimens which had 1.5 times larger dimensions of NA specimens, named NA-M specimens, were used for microscopic observation near the notch root.

2.2. Fatigue tests

Fatigue tests were performed with a tension–torsion biaxial electro-servo-hydraulic testing machine (Shimadzu EHF-ED10/TQ-40L). Fatigue testing was done under load-controlled conditions with the load ratio R of -1. The waveform of the cyclic load was triangular and the frequency was between 0.2 and 2.0 Hz. The fatigue test under cyclic torsion without static tension is called Case A and that with static tension Case B. The applied shear stress amplitude was expressed in terms of the nominal stress calculated elastically from the applied torque for the minimum cross section. The static tensile stress applied in Case B was the same magnitude as the applied shear stress amplitude. The fatigue test was stopped when the maximum torque drops by 20% from the peak value during fatigue.

The twist angle between the gage length of 25 mm across a notch was measured with an axial torsional extensometer (MTS Model 632.80). The relation between torque and twist angle was recorded with a mobile high-speed wave-recorder (KEYENCE Wave Shot NR-2000) to get data points more than 200 in one loading cycle.

2.3. Electrical potential method

The dc electrical potential method was used to monitor crack initiation and propagation. A direct current of 15 A was flown in the specimen though screws located at points distant from notches. Nickel wires with 0.5 mm in diameter were spot-welded at notch edges and the electrical potential between nickel wires was measured during fatigue testing.

2.4. Microscopic observation

After fatigue tests, the specimen was fractured under tension. Fatigue fracture surfaces were observed macroscopically and also by SEM. The three-dimensional topography was constructed from stereo-pair pictures taken with SEM by using a commercial software, Mex 5.1.

3. Experimental results and discussion

3.1. S–N curves

The relation between the shear stress amplitude and the number of cycles to failure of SUS316L for Case A is shown in Fig. 2a. It should be noted that the fatigue life becomes longer, as the notch gets sharper and stress concentration factor larger. This anomalous notch-strengthening is more evident for the cases of 180 and 160 MPa. The S–N relation for Case B with superimposed static tension is shown in Fig. 2b. In this case, the life of notched specimens

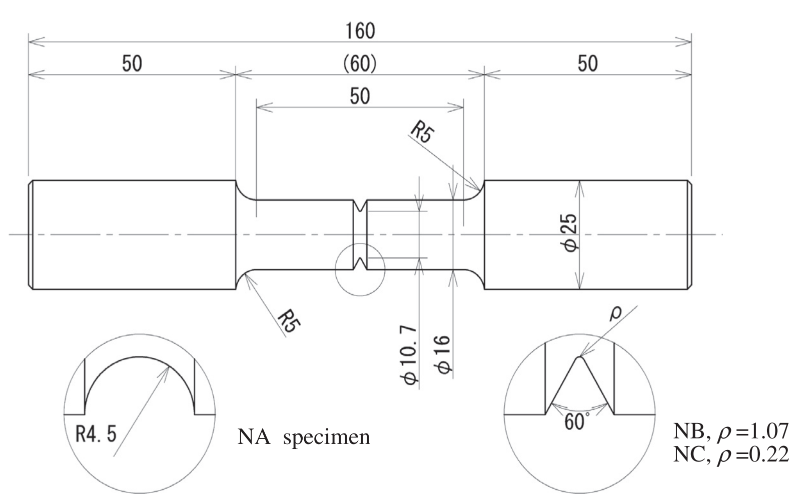

Fig. 1. Shape and dimensions of notched specimens (dimensions are in mm).