Analytical and experimental investigation on crack generated in diameter-enlargement section

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Abstract

We have proposed a new cold processing method to enlarge the diameter of a short section of a metal shaft using a combination of a cyclic bending load and an axial compressive load that is lower than the yield stress of the sample material. We call this cold processing method the diameter-enlargement working method, and refer to the enlarged section of the processed shaft as the diameter-enlargement section. The processing method easily produces large plastic deformation in the processed section under a low axial compressive load at room temperature. However, a crack is sometimes generated in the stepped section during processing. Therefore, we conducted processing experiments to clarify the crack generation conditions, and simulated the working process using the finite element method to investigate the behaviors of stress and strain during processing. Based on the experiments and analyses, we determined that a fatigue crack is generated because of cyclic axial normal stress in the root of stepped section at the axial-compressive loading side. The experimental and analytical fatigue strength was well described by the Coffin-Manson expression.

Keywords: Crack, Diameter-enlargement working method, Low cycle fatigue damage, Finite element method

Introduction

We have proposed a new cold processing method to enlarge the diameter of a short section of a metal shaft using a combination of a cyclic bending load and an axial compressive load that is lower than the yield stress of the sample material. We call this cold processing method the diameter-enlargement working method, and refer to the enlarged section of the processed shaft as the diameter-enlargement section [1-3]. The key features of this processing method are as follows: First, the diameter-enlargement deformation progresses easily under a low axial compressive load at room temperature through the Bauschinger effect (also referred to as the mechanical ratchet phenomenon) arising from alternate stresses caused by the cyclic bending load during processing. Second, although the processing causes large plastic deformation, the processed shaft exhibits little temperature increase. Finally, material wastage does not occur because no waste particles are generated as in cutting operations. We have previously clarified the influence of the processing conditions, such as the axial-compressive load, bending angle, and rotating speed, as well as the mechanical properties of the sample materials in terms of diameter-enlargement deformation behavior [4-7]. From this previous research, it was determined that the plastic deformation progresses as the rotating speed increases. However, crack generation occurs at the notch root near the diameter-enlargement section according to the processing conditions that causes the test specimen to break for reasons that are not yet clear. Therefore, this present study experimentally and analytically investigated the conditions of crack generation at the notch root. First, we conducted processing experiments to investigate the point in the process where crack initiation occurs, thereby evaluating the limiting number of rotations for crack initiation for different processing conditions. Second, we conducted low-cycle fatigue tests to obtain a repeated stress-strain curve, which was applied to elasto-plastic

Table 1 Mechanical properties of the sample material

Young's modulus E (GPa)	210
Yield stress σ_y (MPa)	580
Tensile strength σ_b (MPa)	735
Percentage reduction of area φ (%)	37.6

Table 2 Processing conditions

Axial-compressive force P (kN) (Normalized stress σ_c/σ_y)	46, 69, 91 (1.0, 1.5, 2.0)
Bending angle θ (degree)	2, 3
Rotating speed ω (rpm)	60
Radius of notch root r (mm)	2

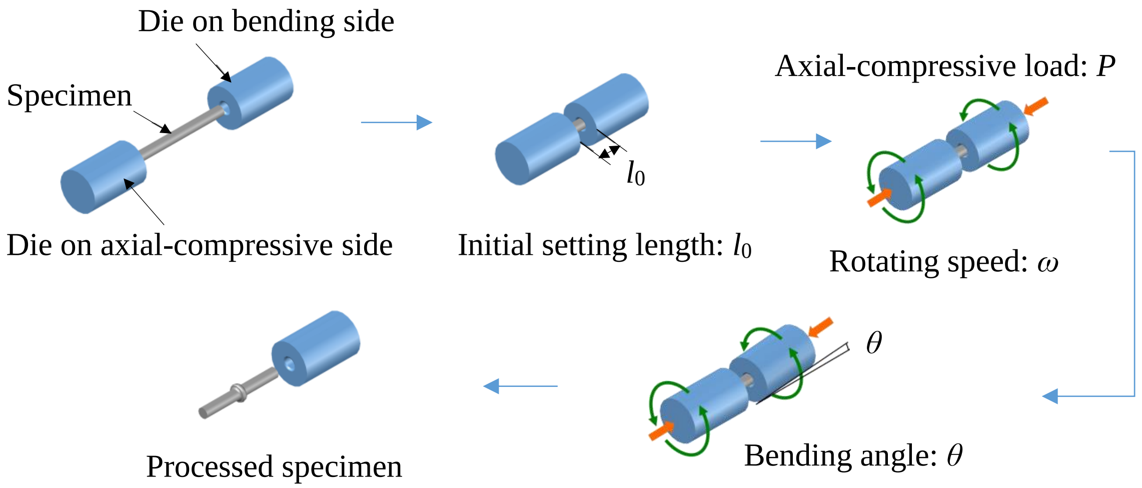

Fig. 1 Diameter-enlargement working procedures

numerical analyses. Using the finite element method (FEM), we simulated the stress and strain behaviors in the processed shaft in the vicinity of the diameter-enlargement section during processing, and calculated an elasto-plastic stress concentration factor, an elasto-plastic strain concentration factor, and a fatigue strength reduction factor. Finally, we evaluated the fatigue strength of the processed shaft using the Manson-Coffin expression.

Processing experiments and finite element analyses for calculating stresses

Experiments

Experiments were done by using the machine developed originally, Cold drawing steel SS400 (Japan Industrial Standard) was used for the experiments. Its material properties are described in Table 1. Table 2 lists the processing conditions, Fig. 1 illustrates the experimental procedures. First, a smooth specimen is coaxially placed between the bending side and the axial-compressive side dies with the distance defined as an initial setting length l_0, and an axial-compressive force P is loaded on the test specimen. Next, keeping the load P constant, the specimen is rotated with a rotating speed ω while simultaneously setting a bending angle θ on

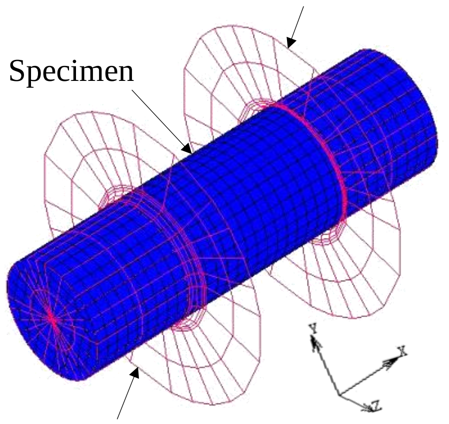

Fig. 2 Analysis model

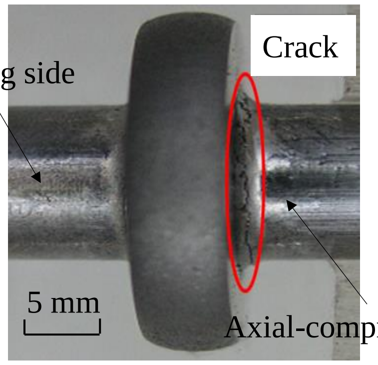

Fig. 3 Processed specimen exhibiting crack formation near the stepped section

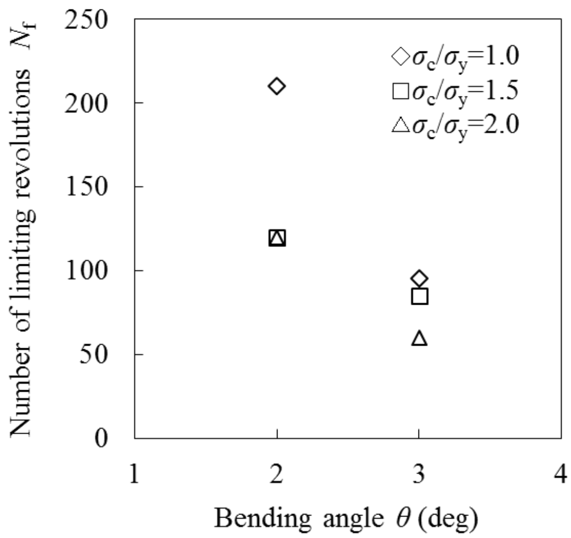

Fig. 4 Number of limiting revolutions under each processing condition

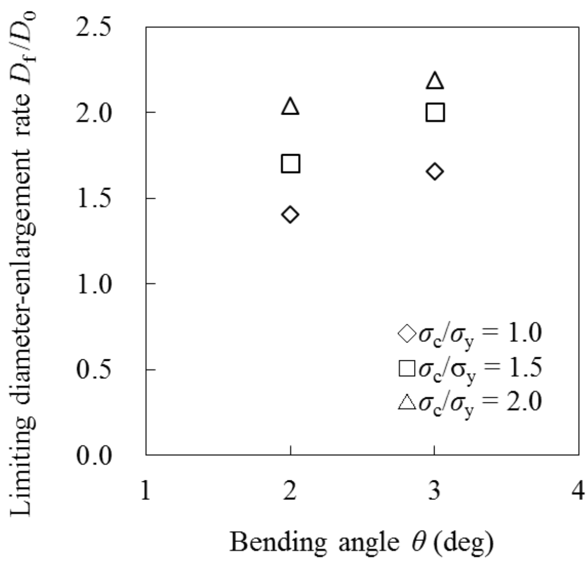

Fig. 5 Limiting diameter-enlargement rates under each processing condition

the specimen. When the diameter of the diameter-enlargement section reaches the target diameter, the application of the bending angle and rotation is stopped.

Analyses

Finite element analyses were carried out for simulating the processing. Fig. 2 shows a three-dimensional model with the same dimension as the specimen using eight node isoparametric elements. The specimen is modeled as a deformable body, whereas the dies are rigid bodies. Number of nodes is 6240 and number of elements is 5504. Type of contact interaction between specimen and die is touching. The friction force is calculated based on the shear friction rule. The coefficient of friction is assumed to be 0.15. A bending angle θ and a rotating speed ω are applied to the bending die, and an axial compressive force P and the same rotational speed ω are applied to the pressure die. The von Mises yield criterion, kinematic hardening law considering the Bauschinger effect, and Prandtl-Reuss's flow rule are adopted. The relation between the actual stress σ and the plastic strain ε_p, obtained by the low-fatigue tests, is expressed by Eq. 1:

$$\sigma = K{\varepsilon_p}^n \tag{1}$$

where K is a material constant set at 1100, and n is the cycle strain hardening factor with a value of 0.25. FEM analyses were performed under the same loading conditions as the processing experiments using commercial nonlinear finite element software (MSC. Marc Mentat 2013.0.0).

Experimental and analytical results and discussion

Process limitations

A perpendicular crack in the axial direction occurs near a notch root on the axial-compressive load side, and the specimen breaks owing to compressive deformation when the rotating speed is increased. Fig. 3 shows an image of the resulting crack formation. We define the number of revolutions prior to when a crack occurs as the number of limiting revolutions N_f, and this is shown in Fig. 4 for the various processing conditions considered (Table 2). The diameter-enlargement rate at the time of crack generation is defined as the limiting diameter-enlargement rate D_f / D_0, and this is shown in Fig. 5 under the various processing conditions. The limiting diameter-enlargement rate increases with increasing bending angle and axial-compressive loading, but the number of limiting revolutions decreases. The main reason is that diameter-enlargement deformation advances fast because of the Bauschinger effect when the bending angle increases. And the alternating stress amplitude of tension-compression, loaded on the processed part, increases, so it becomes easy to generate the fatigue failure, number of limiting revolutions becomes small.

Behaviors of stresses and strains during processing

Figure 7 shows the axial stress behavior, the largest stress component near the notch root on the bending side is the axial normal stress σ_x. And Fig. 8 shows the strain distribution during processing, the axial strain ε_x the axial-compressive loading side changes from compression deformation to tensile deformation after 40 revolutions. On the other hand, the axial strain ε_x on the bending side represents compression deformation during the processing. Therefore, based on the results, a fatigue crack is generated because of the cyclic axial normal stress in the

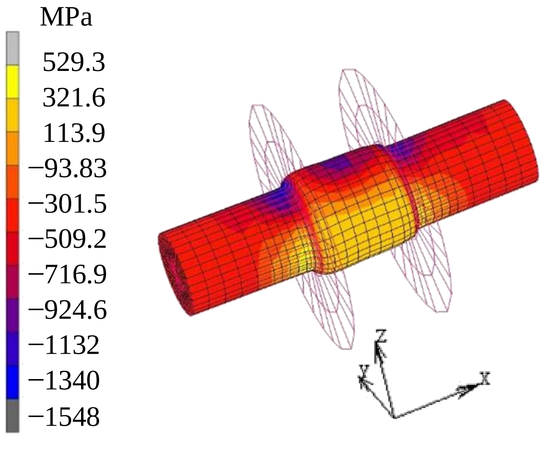

Fig. 7 Axial normal stress (σ_x) distribution under P = 46 kN, θ = 2 degree, and N = 20

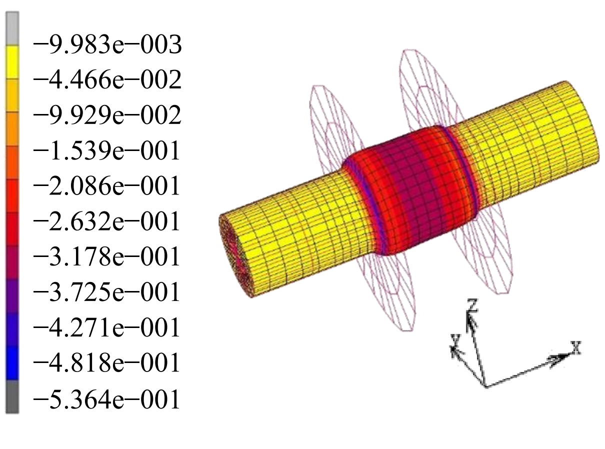

Fig. 8 Axial normal strain (ε_x) distribution under P = 46 kN, θ = 2 degree, and N = 20

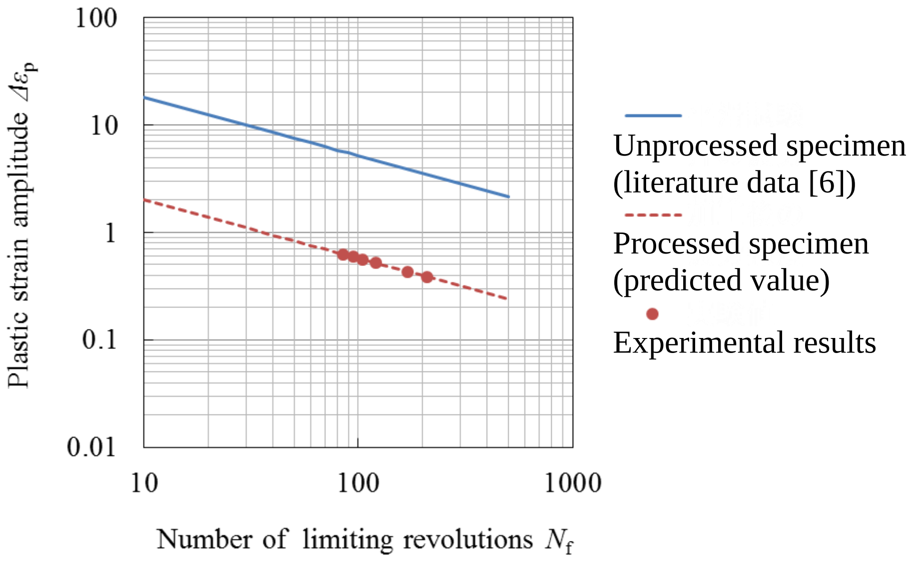

Fig. 9 Fatigue curve.

root of the axial-compressive loading side and not the bending side. The crack develops perpendicular to the specimen axis, and the test specimen breaks. This estimation is demonstrated by the experimental results as well.

Fatigue strength of the processed shaft

The solid line in Fig. 9 shows the fatigue strength of an unprocessed specimen, and the dashed line and filled symbols show the analytical and experimental results, respectively. These plastic strain amplitudes $\Delta\varepsilon_p$ can be expressed well by the Coffin-Manson law [8], as given by Eq. 2:

$$\Delta\varepsilon_p\left(N_f{}'k_f\right)^{K_p} = C_p \tag{2}$$

where k_p is the fatigue ductility index with a value of 0.54 [6], C_p is the fatigue ductility coefficient with a value of 62.2 [6]. k_f is the fatigue strength reduction factor with a value of 5.8, calculated from the elastic-plastic stress concentration coefficient and the elastic-plastic strain concentration factor based on FE analyses, and N_f' is the fatigue strength of the processed specimen and calculated on the basis of the minor rule. The predicted values shown in Fig. 9 correspond very well to the experimental values.

Conclusions

The present study has clarified the mechanism of fatigue crack generation during the diameter-enlargement method processing, and evaluated the conditions of fatigue damage of a processed shaft using the fatigue strength reduction factor. We determined that a fatigue crack is generated because of cyclic axial normal stress in the notch root at the axial-compressive loading side. The experimental and analytical fatigue strength was well described by the Coffin-Manson expression.

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