Fatigue damage in diameter-enlargement part formed by cyclic bending and axial compressive Load

Xia Zhu\textsuperscript{a\#}, Kenichiroh Hosokawa\textsuperscript{b}, Keiji Ogi\textsuperscript{a}, Manabu Takahashi\textsuperscript{a}, Nagatoshi Okabe\textsuperscript{a}

\textsuperscript{a} Dept. of Mechanical Engineering, Ehime University, 3 Bunkyo-cho, Matsuyama, 790-8577, Japan
\textsuperscript{b} Ehime University, 3 Bunkyo-cho, Matsuyama, 790-8577, Japan

Abstract

We proposed a new cold processing method to partially enlarge the diameter of a shaft with a combination of a cyclic bending load and an axial compressive load that is lower than the yield stress of sample material. We call this cold processing method a diameter-enlargement working method, and call this processed part a diameter-enlargement part. Key features of the processing method are chiefly as follows: the diameter enlargement deformation progresses easily under a low axial compressive load at room temperature; the processed part has little temperature increase, although the processing causes large plastic deformation. We have tested the influence of the processing conditions and the mechanical properties of the sample materials in terms of diameter enlargement deformation behavior. However, little is known about the fatigue damage condition in a diameter-enlargement part. Therefore, we carried out processing experiments to clarify crack generation conditions, and simulated working processing using finite element method in order to investigate behaviors of stress and strain during the processing. Furthermore, we evaluated low cycle fatigue damage in the processed part by using the Manson-Coffin expression. This paper clarified the mechanism of crack generation during the processing and evaluates the fatigue strength of the processed part.

\# Xia Zhu. Tel.: +81-89-9279717; fax: +81-89-9279717.
\textit{E-mail address: zhu.xia.mx@ehime-u.ac.jp}

Keywords: low cycle fatigue damage, crack, diameter-enlargement working method, finite element method, stress concentration, notch
1. Introduction

We proposed a new cold processing method to partially enlarge the diameter of a shaft with a combination of a cyclic bending load and an axial compressive load that is lower than the yield stress of sample material. We call this cold processing method a diameter-enlargement working method, and call the processed part a diameter enlargement part by Iura et al. (1999). The key features of the processing method are, as follows: First, diameter enlargement deformation progresses easily under a low axial compressive load at room temperature, through the Bauschinger effect or mechanical ratchet phenomenon, arising from alternate stresses caused by the cyclic bending load during processing. Secondly, the processed part has little temperature increase, although the processing causes large plastic deformation. Finally, this processing does not waste material because it does not generate sawdust as cutting does. We have clarified the influence of the processing conditions, such as the axial-compressive load, the bending angle, and the rotating speed, and the mechanical properties of the sample materials in terms of diameter enlargement deformation behavior by Iura et al. (2002, 2003, 2004). At the same time, we have found that the plastic deformation progresses as the rotating speed increases from the above-mentioned research. However, a crack occurs at a notch root near a diameter enlargement part according to processing conditions and the test specimen breaks. Therefore, this paper investigated experimentally and analytically the fatigue strength at the notch root under each processing condition. First, we carried out rotary processing experiments to investigate the position of crack initiation and limiting rotating speed of crack initiation. Secondly, we did low-cycle fatigue tests to obtain a repeated stress strain curve applied to elasto-plastic numerical analyses. Using finite element method (FEM), we simulated the behaviors of stress and strain in the processed part during processing, and calculate 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 part using the Manson-Coffin expression.

2. Processing experiments and simulated FEA

2.1. Processing machine and processing procedures.

The processing machine developed originally is shown in Fig. 1. It is composed of three main parts: an axial rotary actuator; axial compressive load parts; and bending parts. Structural carbon steel SS400 (Japan Industrial Standard) was used for processing experiments. Its material properties are shown in Table 1. A specimen has $D_0 = 10$ mm in diameter and $L_0 = 48$ mm long. Processing conditions are shown in Table 2.

Processing procedures are shown in Fig. 2. First, a smooth specimen is installed coaxially between the dies of the axial rotary actuator and axial compressive load, and an axially compressive force $P$ is loaded on the test specimen. Next, keeping the load $P$ constant, the specimen is rotated with rotating speed $\omega$ while setting a bending angle $\theta$ on the specimen at the same time. When the diameter of the processed part reaches the target diameter, the bending angle and rotation are turned off.

![Fig. 1 Processing machine.](a) General view.  
(b) Dies.
Table 1 Mechanical properties of the sample.

| Property                        | Value |
|---------------------------------|-------|
| Young’s modulus $E$ (GPa)       | 210   |
| Yield stress $\sigma_y$ (MPa)   | 580   |
| Tensile stress $\sigma_t$ (MPa) | 735   |
| Percentage reduction of area $\varphi$ (%) | 37.6  |

Table 2 Processing conditions.

| Condition                                | Value       |
|------------------------------------------|-------------|
| Axial-compressive force $P$ (kN)         | 46, 69, 91  |
| (Normalized stress $\sigma_c / \sigma_y$)| 1.0, 1.5, 2.0|
| Bending angle $\theta$ (degree)          | 2, 3        |
| Rotating speed $\omega$ (rpm)            | 60          |
| Radius of notch root $r$ (mm)             | 1, 2        |

Fig. 2 Diameter-enlargement working procedures.

Fig. 3 Analysis model.

Fig. 4 Stress vs. strain curve.
2.2. Low cycle fatigue testing

To obtain a repeated stress strain curve, low cycle fatigue tests were done in an axial strain control. Specimens were made based on JIS Z 2279:1992. Strain amplitudes were 3%, 5%, 7%, 10% and 15%. A loaded strain rate was 0.0001 m/sec.

2.3. Simulation analysis solution to stress and strain distribution using FEM

Figure 3 shows a three-dimensional model with an eight nodes isoparametric element. Specimen is a deformable body, and dies are rigid bodies in the model. The von Mises yield criterion, kinematic hardening law considering the Bauschinger effect, and Prandtl-Reuss's flow rule are adopted respectively. A curve of stress vs. strain is shown in Fig.4 using the simulation analysis. A bending angle $\theta$ and a rotating speed $\omega$ are loaded on the left die, and an axial compressive force $P$ and the same rotational speed $\omega$ are loaded on the right die. The friction force is calculated based on the shear friction rule. Coefficient of friction is assumed to be 0.15. Simulation analyses were done under the same loading conditions as the processing experiment using commercial FE software (MSC. Marc Mentat 2013.0.0).

3. Experimental and analytical results and discussion

3.1. Position of crack initiation and number of limiting revolutions of crack initiation

A perpendicular crack to axial direction occurs on the axial-compressive side, and a specimen breaks though a compressive deformation advances when the rotating speed is increased. Fig. 5 shows a crack. A number of limiting revolutions is defined to a number of revolutions when a crack occurs, and is shown in Fig. 6 under various processing conditions. A compressive deformation progresses quickly as a bending angle and an axial-compressive become large, but a number of limiting revolutions becomes small.

3.2. Behavior of stress and strain in the processing

Figure 7 shows a stress distribution and Fig. 8 shows a strain distribution in the processing under the condition of $P = 46$ kN, $\theta = 2$ degree and $N = 20$, as an example. Fig. 9 shows stress behaviors and Fig. 10 shows strain behaviors near two notch roots. A cyclic axial stress $\sigma_{xx}$ is the largest as shown in Fig. 9. An axial strain $\varepsilon_{xx}$ in the axial-compressive loading side changes from the compression deformation to the tensile deformation after 40 revolutions. And the other hand, an axial strain $\varepsilon_{xx}$ in bending side is a compression deformation during all
processing. Hence, a fatigue crack is generated due to the cyclic axial normal stress in the notch root of the axial-compressive loading side not the bending side, based on above-mentioned. The crack develops in a perpendicular direction to axial, and the test specimen breaks. The guess is demonstrated even by the experimental results.
3.3. Fatigue damage in a fillet during processing

A fatigue strength decreases in a notch root due to stress concentration during the processing. Then, a fatigue strength reduction factor $K_f$, shown in expression (1), is calculated based on the FEM analysis results.

$$K_f = \frac{\sigma_f}{\sigma_n} \cdot \frac{\varepsilon_f}{\varepsilon_n} \quad (1)$$

Where $\sigma_f$ is a partial elastic-plastic stress and $\varepsilon_f$ is a partial elastic-plastic strain at a notch. $\sigma_n$ is a nominal stress and $\varepsilon_n$ is a nominal strain in a notch cross section.

Figure 11 shows a fatigue strength $N'_f$ of the processed specimen, expressed by the Coffin-Manson rule, and calculated based on the fatigue strength $N_f$ of an original specimen and fatigue strength reduction factor $K_f$.

$$\Delta \varepsilon_p (N'_f K_f)^{k_p} = C_p \quad (2)$$

Where $k_p$ is a fatigue ductility index and $C_p$ is a fatigue ductility coefficient. In addition, the fatigue strengths calculated by using the coefficient of linear cumulative damage are corresponding to experimental measurements well.

4. Summary

The present study has clarified the mechanism where the fatigue crack is generated during the processing, and evaluated the fatigue damage situation of a processed specimen by using the fatigue strength reduction factor.

References

Iura, T., Mori, K., Yamamoto, K., Aono, Y., Kurita, K., Nakamura, O., and Sano, T., 1999, LOCAL COLLAR DEVELOPED BY METAL PLASTIC DEFORMATION, Proc. 6th ICTP, 613-618.

Okabe, N., Zhu, X., Iura, T., and Mori, K., 2002, Model Analysis for a Clod Working of Collar-forming in a Metal Bar with Local Superplastic Deformation by a New Conceptual Technology, Proc. 7th ICTP, 871-976.

Iura, T., Okabe N., and Zhu, X., 2003, Development of Novel Plastic Working Process for Producing a Collar on a Round Shaft, Journal of the JSTP, Vol.44, No.514, 45-49.

Iura, T., Okabe N., and Zhu, X., 2004, Generation of Bending Moment and Twist Torque and Temperature Increase during the Working Process for the Production of a Collar in a Round Bar, Journal of the JSTP, Vol.45, No.516, 35-39.

The Japan Society of Mechanical Engineers, 1983, JSME Data Book: Fatigue of Metals, 4, Low Cycle Fatigue Strength, Maruzen Publishers, 9-15, 147, 179.