FATIGUE DAMAGE OF SHAFT WITH THE COLLAR FORMED BY A NEW DEFORMATION PROCESSING METHOD FOR ENLARGING PARTIAL DIAMETER

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ABSTRACT

We have proposed a new deformation processing method for enlarging partial diameter of shaft. The method is called a collar-forming method. To examine fatigue damage of the part processed (called a collar) during the forming process, rotary bending fatigue tests and tensile strength verification tests were carried out on smooth test specimen as well as two kinds of collared test specimen, namely the specimen with burrs and without burr. Moreover, stress concentration and strain hardening in the root of collar were quantitatively evaluated by the finite element method. The following were clarified from those results: Though there are burrs, the fatigue damage in the root of a collar during the forming process is not caused at all when an increase rate of shaft diameter is within 1.7. The processing stage in which the increase rate is within 1.7 is still a stage of the work hardening, and is not a stage in which the fatigue life is shortened by increasing of macro-damage. There are not any signs of fatigue deterioration in the root of collar formed by the processing method from a practical viewpoint, either but there is sound to the fatigue damage enough.

1 INTRODUCTION

We have proposed a new deformation processing method to enlarge the partial diameter of shaft by combining a cyclic bending stress and axial-compressive stress that is lower than the yield stress of material used. The processing method is a called collar-forming method and the processed part is called a collar [1]. The features of the deformation processing method, in which the mechanical ratchet phenomenon is used, are as follows: A compressive deformation progresses easily under a low-compressive load at room temperature, through the Bauschinger effect arising from alternate stresses during the processing process; there is little temperature-rise in the collar though a large-plastic deformation is generated [2-5]. However, little is known about fatigue properties of the collared part. It is important to clarify whether fatigue damage occurs during the processing process. It is necessary to investigate fatigue properties of the collar root formed by the processing method, and it is necessary to clarify whether the fatigue properties are affected by burrs, which are generated by adoption of zipper divided in three to take priority over considering work efficiency. In the present research, rotary bending fatigue tests and verification tests of remaining strength were carried out on smooth test specimen as well as two kinds of collared test specimen which are pecimen with burrs and one without burr. Moreover, stress concentration and strain hardening in the root of collar were quantitatively evaluated though the stress analysis by the finite element method (FEM).

2 EXPERIMENTS

2.1 Experimental apparatus and test specimen

A processing machine is shown in Fig.1. It is composed of three main parts: axial-rotary drive; axial-compressive load parts; bending angle-setting parts. Round bars of cold drawing steel

SGD400 (Japan Industrial Standard) were used to the processing experiments. The diameter of bar D_0 is 10mm. A collared specimen was produced by the following procedures: it was installed coaxially between both zippers of axial-rotary driving side and axial-compressive load side, an axial-compressive force P was loaded on the test specimen; keeping on putting a constant axial-compressive load P, the test specimen was rotated, a bending angle θ was set on the test specimen at the same time; After the collar had been formed following in a schedule, the bending angle θ was returned to 0 rad. Six kinds of collared test specimens with different increasing rates of diameter $\xi=D/D_0$=1.3, 1.4, 1.5, 1.6, 1.7 and 1.8 were produced following in the procedures as mentioned above, where D is the final diameter of the collar. C_1 test specimen has thin burrs, but C_2 test specimen hasn't it as shown in Fig.3.

2.2 Rotary bending fatigue tests

High-cycle fatigue tests were carried out on a collared specimen under the condition of rotational speed ω of 600 rpm at room temperature in atmosphere using a rotary bending testing machine of cantilever. On the other hand, low-cycle fatigue tests were carried out on a collared specimen under the condition of rotational speed of 10 rpm, by giving the bending angles of θ=0.035rad-0.14rad the collar-forming processing machine against rotational axis. High-cycle fatigue tests on smooth test specimens were also done, while putting a copper pipe of 2mm in radial thickness between zipper and the specimen to release stress concentration in the part chucked, and a part of experimental apparatus is shown in Fig.4.

2.3 Tensile tests to evaluate residual fracture strength

In order to clarify the progressive state of fatigue damage in the process and the limit of the enlarging, the verification tests to evaluate a residual fracture strength were done by the following procedures: all collared specimen used to present test were produced until the final increasing rate of diameter become about ξ=1.7; The axial-compressive force P was unloaded, a space l_b=10mm was left between the edge of collar and the zipper of axial-compressive load side, and a bending angle θ=0.105rad was given; a low-cycle rotary test was carried out on the collared specimen under the condition of $\Delta\sigma$=583MPa, and it was stopped before breaking of the collared specimen;

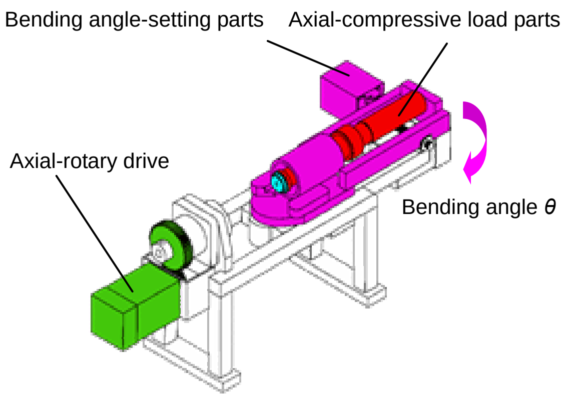
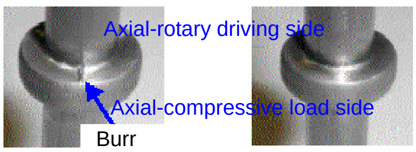


Fig.1 Bird's-eye view of a collar-forming apparatus used



(a) C_1-specimen (b) C_2-specimen

Fig.3 Photograph of collared specimen

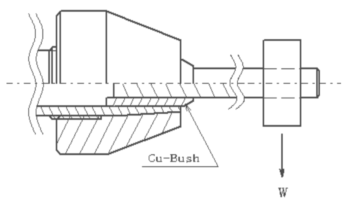


Fig.4 Rotary bending test on a smooth test specimen

a tensile test was done on the same collared specimen, the fracture surface was observed with the microscope.

3 EXPERIMENT RESULTS AND DISCUSSION

3.1 Fatigue properties obtained by rotary bending tests

S-N diagrams of smooth specimen and collared specimen without burr obtained by a high-cycle fatigue tests are shown in Fig.5. Fatigue properties of collared specimen with burrs obtained by a high-cycle fatigue tests is shown by a cycle marks in Fig.6, and approximated lines are also shown by a solid line in Fig.6. Moreover, all crack initiations of fatigue fracture were observed in root of collar in the axial-compressive side. The fatigue properties are approximated by the next expression.

$$\sigma = 10^{\{-A\log N + B\}} + C_1 \tag{1}$$

Where A, B and C are material constants respectively. It is shown in Fig.5 that fatigue strength of collared specimen is lower than one of smooth specimen. Moreover the fatigue damage was examined as follows. An elastic-plastic analysis on the stress concentration in the root of collar was done by using finite element method (FEM). It is clear from analytic results that there are few differences of the stress distribution in the root of collar in spite of different increasing rates of diameter ξ. Moreover, the factor of stress concentration α_1, which depends upon diameter D_0 and curvature radius ρ_R in the root of collar, can be presumed by the next expression.

$$\alpha_1 = 1 + K\left(D_0/2\rho_R\right)^{n_1} \tag{2}$$

Where K=0.3, n_1=-0.6434. The relations between α_1 and ρ_R/D_0 are nearly constant and are independent of the increasing rate of diameter ξ as shown in Fig.7. It is well known that a notch coefficient β_1 can be given by the next expression to evaluate the deterioration of fatigue strength due to the stress concentration.

$$\beta_1 = 1 + \eta\left(\alpha_1 - 1\right) \tag{3}$$

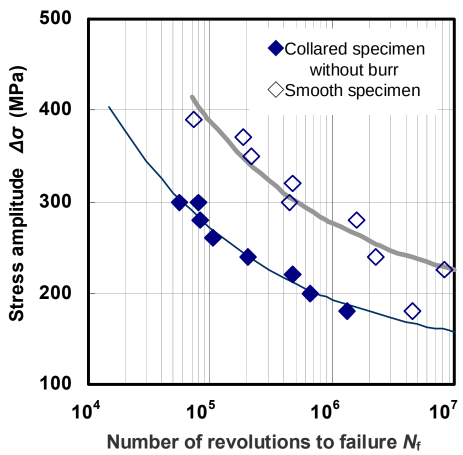


Fig.5 S-N diagram of smooth specimen and collared specimen

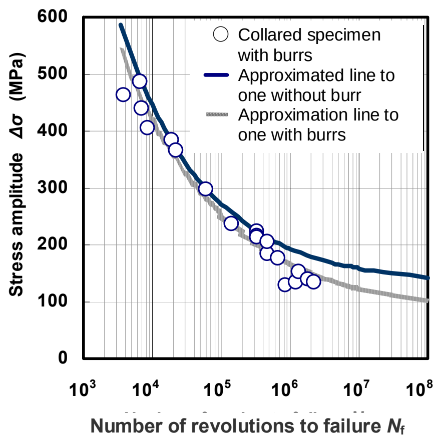


Fig.6 Effect of burr in root of collar on fatigue strength

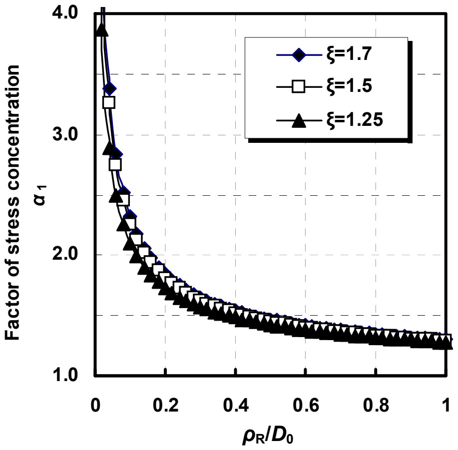


Fig.7 Stress concentration diagram by relation between α_1 and ρ/D_0 as a parameter of ζ

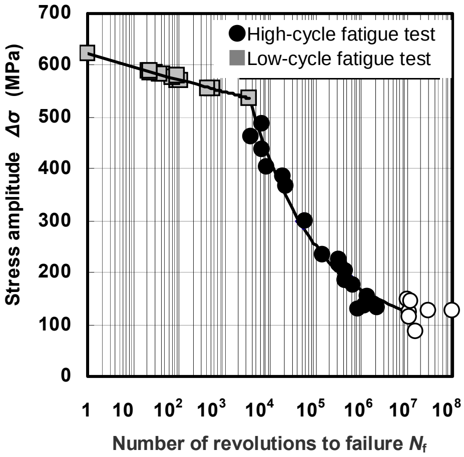


Fig.8 S-N diagram in whole life regions

Where η is a sensitivity coefficient and is 0.5 in the case of yield stress σ_y below 500MPa. From both values of the shape of collared part and the yield stress of material used, it can be calculated that the stress concentration factor α_1 is 1.845 and notch coefficient β_1 is 1.43, and then it can be estimated that fatigue strength of the collared test specimen is $1/\beta_1$=0.7 times as much as one of a smooth test specimen due to notch in the collared part, the estimated strength corresponds well to experimental results as shown in Fig.5. And so it could be experimentally verified that the fatigue damage due to cyclic bending stress does not occur during the collar-forming process. However, the burrs in the root of collar, which becomes starting point of crack, give rise to a little decrease in fatigue strength in the region of $N_f>10^6$ as shown in Fig.6. The S-N diagram of whole region shown in Fig.8 including the low-cycle region, is approximated by the next expression.

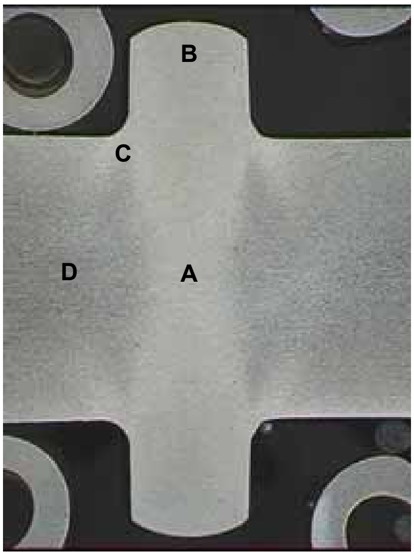
$$\Delta\sigma N_f^{\,n_2} = C_2 \tag{4}$$

Where n_2 is a fatigue damage index and C_2 is strength constant.

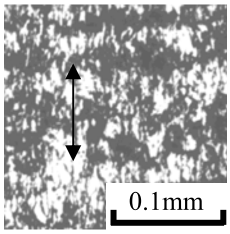
3.2 Microscopic morphology and work hardening during the collar-forming process

The flow of a microscopic morphology in the collared part was observed with a microscope. Photograph 1 is morphology of a collar. White crystal grain in the photograph is a ferrite, and black crystal grain is a perlite. It is well known that the morphology, in which the flow of each crystal grain indicates the direction processed, is formed by work hardening during the processing process. The following as shown in Fig.10 are found: Each crystal grain has expanded in the direction of the processing indicated by the arrows; compared with each part of A and B and D, the crystal grain in C part expands more greatly so that the slip deformation progresses more greatly in the part. Results observed from photograph 1 give good agreement with the values that have been calculated by the stress analysis of FEM and measured by Vickers hardness meter shown in Fig.9. Since the maximum Vickers hardness Hv=419.6 in the root of collar is lower than Hv=550 of a smooth test specimen, it can be presumed that the forming process is at a work hardening stage, and it is thought that the fatigue damage is hardly caused to cyclic bending stress.

3.4 Behavior of strength deterioration during a collar-forming process

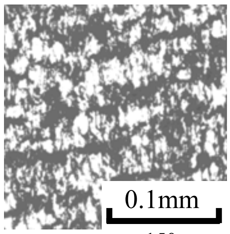


$\xi = D/D_0 = 1.8$ ×15



×150

(a) Enlarged view of A part



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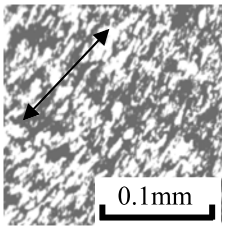
(b) Enlarged view of B part



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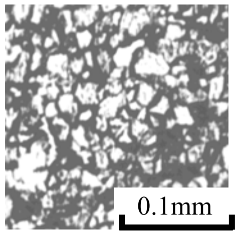
(c) Enlarged view of C part



×150

(d) Enlarged view of D part

Photograph 1 Microscopic morphology of a collared

Tensile tests to evaluate residual fracture strength were conducted and their results are shown in Fig.10. Residual tensile strength of collared specimen $\sigma_{BN'}$ normalized with the tensile strength σ_{B0} of smooth specimen is indicated in vertical axis. As shown in Fig.10, the residual tensile strength starts to decrease slowly since 5 rotations in the low-cycle fatigue test because a very small crack occurs in root of collar and decreases sharply since 20 rotations in the low-cycle fatigue test because the crack grows and drops markedly after 35 rotations in the low-cycle fatigue test because the crack grows to a penetrating crack. The residual fracture strength obtained by the tests is corresponding well to estimated strength by the expression (4). The rupture aspects of tensile tests are shown in Fig.11. The following were observed from the figure: within 5 rotations in the

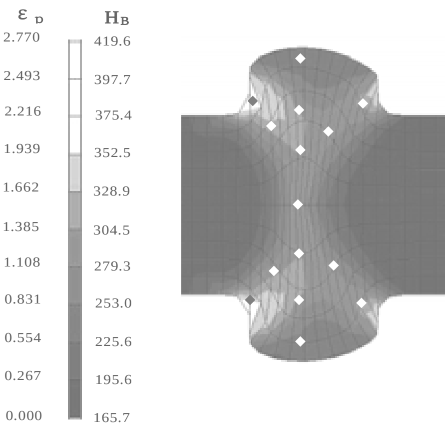


Fig.9 Distribution of plastic strain and Vickers hardness in a collar

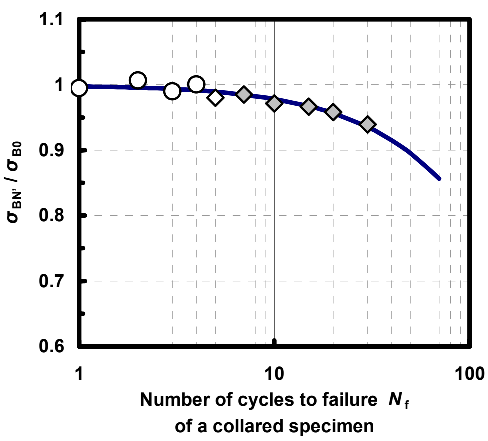


Fig.10 Strength degradation and remaining life of collared specimen

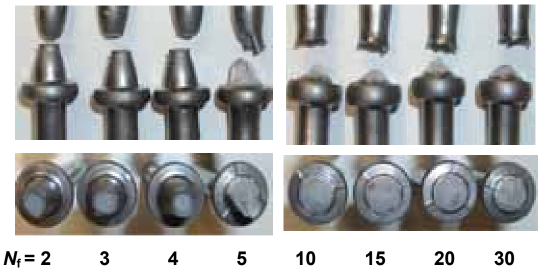


Fig.11 Fracture surface by tensile test after a low-cycle fatigue tests

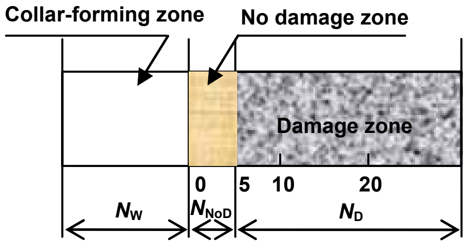


Fig.12 Scheme of a fatigue damage progressing

low-cycle fatigue test, fracture positions are away from the root of collar, a crack is not found in the fracture surface of tensile tests; however, since 6 rotations in the low-cycle fatigue test, fracture positions are in the root of collar, a crack arising from deterioration in strength is observed on the fracture surface. As observed above, it is understood that the fatigue damage is not caused during the collar-forming process of increasing rate in diameter ζ=1.7, under the processing condition of axial-compressive stress $\Delta\sigma_c$=583MPa and bending angle θ=0.105rad, in the case of that the collared specimen is rotated within four rotations in the low-cycle fatigue test. The progress of strength deterioration is illustrated in Fig.12.

4. CONCLUSION

In the study, the fatigue properties and fatigue damage of collared specimen is discussed experimentally and analytically from a viewpoint of practical use. The results obtained are as follows. Though there are burrs, the fatigue damage at the root of collar during the collar forming process is not caused at all when an increasing rate of shaft diameter is within 1.7; The collar forming process, in which the increasing rate is within 1.7, is still a stage of the work hardening, and is not a stage in which the fatigue strength starts to decrease; There are not any signs of fatigue deterioration in the collar formed by the processing method from a practical viewpoint, either but there is sound to the fatigue damage enough.

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