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LETTER

Improving the fatigue strength of the elements of a steel belt for CVT by cavitation shotless peening

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The elements of steel belts used for continuously variable transmission (CVT) are subjected to a bending load during operation. The weakest portion of the elements is at the root of the "neck" which works into metallic rings. In order to reduce the stress concentration, the root of the neck is rounded and the shape of element is optimized. Nevertheless, if the fatigue strength of the elements can be improved, the steel belt can be applied to larger engines. Although conventional shot peening is one way of enhancing the fatigue strength, it is very difficult for shot to reach into deep and narrow regions.

Recently, a peening method using the impact produced as cavitation bubbles collapse has been developed [1–9]. This method is called "cavitation shotless peening (CSP)", as shot are not required [3–6, 8]. CSP can peen the surface even through deep narrow cavities, as the bubbles can reach these parts and collapse where peening is required.

In the present article, improvement of the fatigue strength of the elements of a CVT metallic belt by CSP was demonstrated experimentally. Elements were treated with different processing times and evaluated by a fatigue test to find the optimum processing time. In order to evaluate the peening effect by CSP, the residual stress was measured. Note that this is the first report published on the improvement made in the fatigue strength of a part with regions that cannot be hit directly by shot.

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Cavitation shotless peening was applied to the element using cavitating jet apparatus, the details of which can be found in references [3–6, 8]. The jet was injected into the neck region through grooves in the elements, which were stacked and held together, and scanned perpendicularly over the elements, as shown in Fig. 1. The processing time per unit length, t_p, is defined by the number of scans n and the scanning speed v;

$$t_p = \frac{n}{v} \tag{1}$$

The cavitation number,σ, a key parameter for cavitating jets, is defined by the injection pressure, p_1, the tank pressure, p_2, and the saturated vapor pressure, p_v, as follows;

$$\sigma = \frac{p_2 - p_v}{p_1 - p_2} \cong \frac{p_2}{p_1} \tag{2}$$

σ can be simplified as indicated in Eq. 2 because $p_1 \gg p_2 \gg p_v$. Absolute pressure values were used to determine the cavitation number. Considering the results from previous work [3–6, 8], the CSP conditions shown in Table 1 were selected.

The shape of the element tested was identical to actual elements used in steel belts for CVT. The element was made of Japanese Industrial Standards JIS SK5 and was heat treated in the same way as actual elements.

In order to examine the improvements made in the fatigue strength, the residual stress of the elements at position A in Fig. 2 was measured using X-ray diffraction with a two-dimensional position sensitive proportional counter (2D PSPC) using the 2D method [10]. After CSP, part of the element was cut off and put into the X-ray

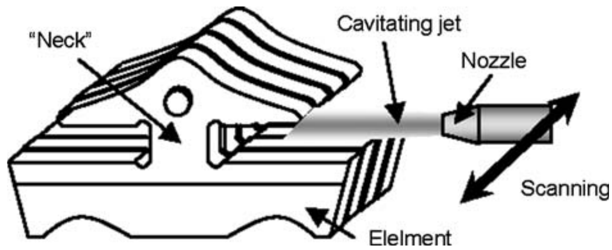

Fig. 1 Setup of the elements treated by CSP

Table 1 CSP conditions

Injection pressure p_1 MPa	30
Tank pressure p_2 Mpa	0.42
Cavitation number σ	0.014
Nozzle diameter d mm	2
Standoff distance s mm	80

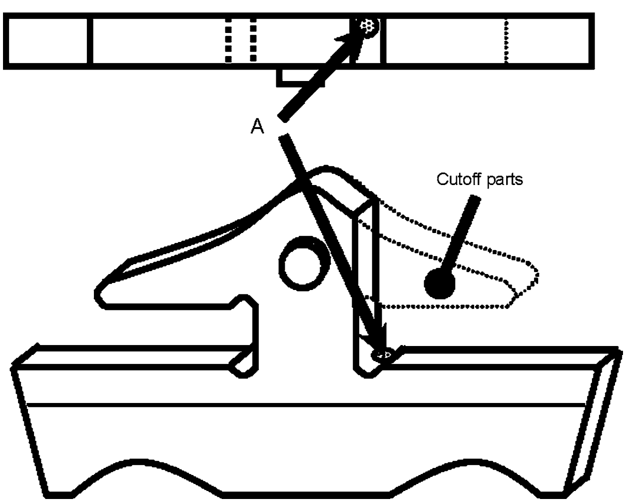

Fig. 2 Measurement position of the residual stress using X-ray diffraction

apparatus to detect diffractive X-rays, as shown in Fig. 2. A Cr tube operated at 35 kV and 40 mA was used. The diameter of the collimator was 0.1 mm. X-rays were counted for 20 min for each frame. The diffractive plane was the (211) plane of α–Fe, and the diffractive angle, 2θ, was about 156 degree. The values used for Young's modulus and the Poisson ratio were 210 GPa and 0.28, respectively. The residual stress in the longitudinal direction of the element was obtained from 13 frames using the 2D method.

In order to evaluate the fatigue strength of the element, a bending fatigue test was carried out on the element, as shown in Fig. 3. As shown in the figure, the element was fixed and a load F was applied perpendicularly.

Figure 4 illustrates the relationship between the number of cycles to failure, N, and the normalized amplitude of the

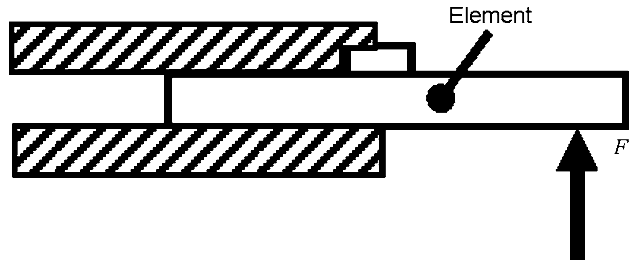

Fig. 3 Schematic diagram of the bending fatigue test of the element

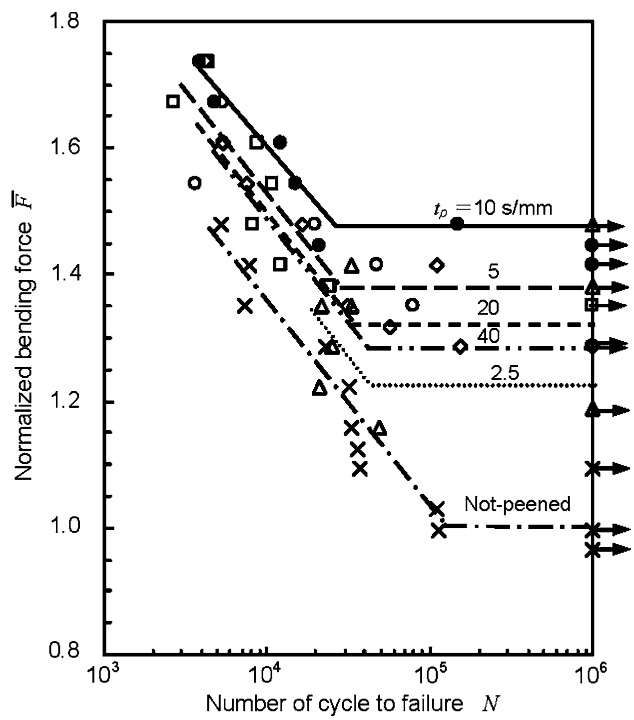

Fig. 4 Improvement of the fatigue strength of the element by CSP

bending force, $\bar{F}$, used in the fatigue test, for various processing times per unit length, t_p. The amplitude of the bending force was normalized by the fatigue strength of the non-peened specimen, which was obtained by Little's method [11]. The fatigue tests were terminated at $N = 10^6$, as it was confirmed that specimens which survived 10^6 cycles also survived 10^7 cycles. From the figure, it is clear that CSP can extend the lifetime of specimens compared to non-peened specimens. The normalized fatigue strength, $\bar{F}_{FS}$, of specimens treated by CSP is 1.22 at $t_p = 2.5$ s/mm, 1.38 at $t_p = 5$ s/mm, 1.48 at $t_p = 10$ s/mm, 1.32 at $t_p = 20$ s/mm, and 1.28 at $t_p = 40$ s/mm, respectively. At $t_p = 10$ s/mm, the fatigue strength of the element has been improved by 48% compared with that of the non-peened element.

Figure 5 shows the normalized fatigue strength $\bar{F}_{FS}$ as a function of CSP processing time per unit length, t_p. $\bar{F}_{FS}$ increases with t_p until $t_p = 10$ s/mm and then decreases

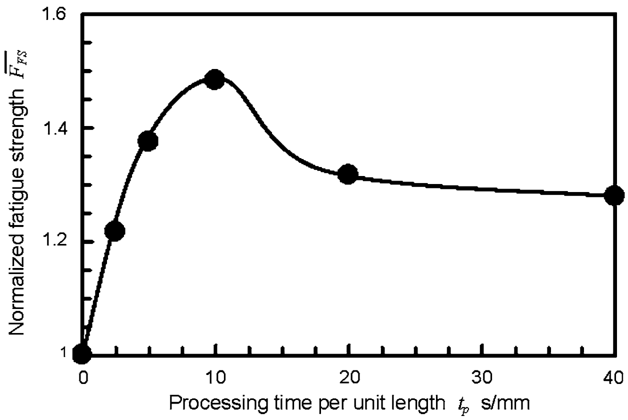

Fig. 5 Optimum CSP processing time per unit length

slightly. This shows that, as with shot peening, there is an optimum processing time, and that too long processing times cause the fatigue strength to decrease. For the conditions applied here, the optimum CSP processing time per unit length was 10 s/mm.

Figure 6 shows the variation in the residual stress of the element at position A in Fig. 2 with processing time per unit length, t_p. In order to evaluate the reproducibility, the residual stress of two elements was measured for each value of t_p using the 2D X-ray diffraction method. Standard deviations for each measurement are shown in Fig. 6. Without CSP, the residual stress was -140 ± 50 MPa and after CSP this was greater than -600 MPa. Thus, CSP can introduce compressive residual stress into the surface even where there are deep and narrow cavities. The impact induced by collapsing cavitation bubbles can introduce compressive residual stress into surfaces that cannot be hit directly by shot (see Fig. 1). The residual stress on the surface increased to between -800 MPa and $-1{,}000$ MPa for short processing times, $t_p = 2.5$ s/mm, then decreased slightly saturating at about -800 MPa, as shown in Fig. 6. According to a previous report [5], the compressive residual stress of the sub-surface in materials increases after the residual stress on the surface has saturated. Thus the compressive residual stress of the sub-surface would increase for $t_p \geq 2.5$ s/mm. This is one of the reasons why the optimum processing time for the present conditions was $t_p = 10$ s/mm, even though the compressive residual stress had reached its maximum at $t_p = 2.5$ s/mm.

In order to increase the fatigue strength of the elements of a steel belt for CVT, the elements were treated by CSP. The fatigue strength of the element was evaluated and the residual stress was measured by X-ray diffraction using a 2D method with a 2D PSPC. It was revealed that the fatigue strength of the element could be improved by 48% by CSP. It was also shown that CSP can introduce compressive residual stress even into the surface of deep and narrow cavities.

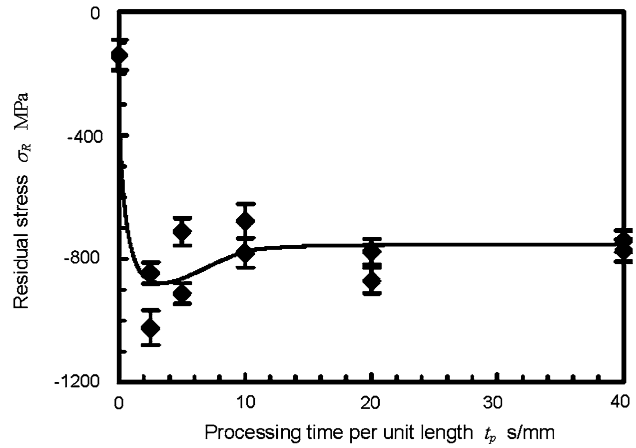

Fig. 6 Introduction of compressive residual stress into the element by CSP

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