

Development of a Spin Forming Procedure for CVT Pulley Covers

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ABSTRACT

The metal pushing V-belt type continuously variable speed transmission (CVT) commonly has a hydraulic chamber that is formed by fastening together the movable pulley and pulley cover parts. The mechanism by which damage occurred to the pulley cover in the spin-formed fastening portion during development was clarified. In order to understand the damage mechanism, the area of the pulley cover subjected to spin forming was examined with a scanning electronic microscope. This revealed that voids had formed inside the examined area, as expected under the theory of ductile fracture, and it was confirmed that durability varied with the form of the voids. Quantitative treatment of the damage was made possible by numerical analysis of the mechanism of void formation using McClintock's equation for damage evaluation. It was further confirmed that the results of this numerical analysis agreed with the results of durability tests of the pulley, verifying the validity of the analytical values.

1. Introduction

At present, many four-wheeled vehicles use metal pushing V-belt type continuously variable speed transmissions (CVT), and various new technologies are being developed for each functional element of the CVT. There is a high demand for measures concerning manufacturing method, cost, weight, etc., related to the pulley, which forms the core of the metal pushing V-belt type CVT.

The CVT pulley system is composed of the movable side and the fixed side. The movable side pulley transmits torque by clamping the belt in the space between it and the fixed side, hydraulically. The force holding the belt is generated by applying hydraulic pressure to the hydraulic chamber formed by the back of the movable pulley. In order to form this hydraulic chamber, it is necessary to connect the pulley and the cover. Connection methods include press fit, spin forming, and tightening by screws, and there are many types

where the pulley and cover are an integrated shape. Among these methods, spin forming is a process whereby the press formed cover is connected to the pulley through plastic forming. It is also an advanced method that has a low production cost. However, research results published concerning connection strength of spin forming are insufficient. In particular, there are almost no quantitative evaluation results concerning the groove shape of the pulley's connecting part and connection strength of the pulley cover.

This research project analyzed the mechanism that was generating cracking in the pulley cover connection part that occurred in the pulley prototype parts, from the material point of view, and at the same time, the generation mechanism was quantified, through numerical analysis. Through this, spin forming connection strength technology was created, making for CVT pulley strength and reliability. This paper reports on the above.

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2. The Aims of Development

Fig. 1 is the main section of a CVT incorporating these results. As shown in the diagram, the pulley cover that forms the hydraulic chamber with both the drive pulley and the driven pulley is connected to the pulleys with spin forming. The spin forming referred to here means the process of pushing in, along the perimeter and using a roller, the cover that turns together with the pulley, as shown in Fig. 2, after the cup-shaped cover is engaged in the movable pulley. In this instance, there is no turning force on the roller doing the machining, but rather while it moves along the cover, there is translation motion in the direction of the cover radius.

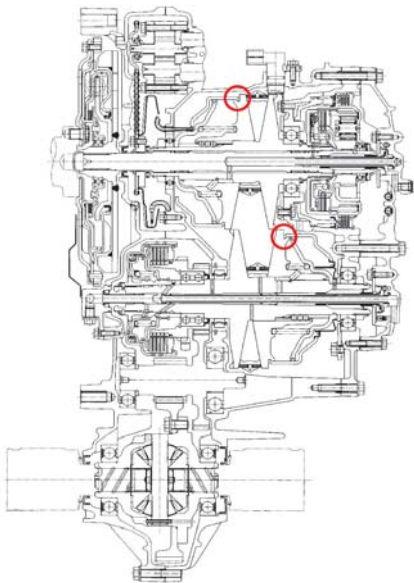


Fig. 1 CVT main section

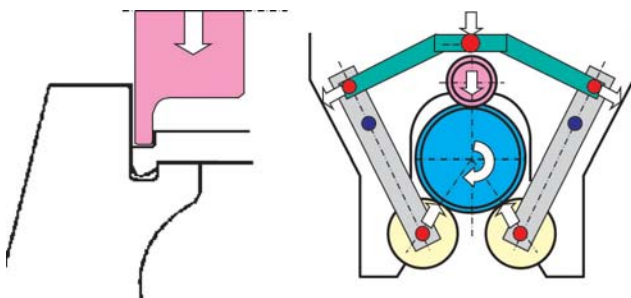


Fig. 2 CVT pulley cover forming

Connection strength in pulley spin forming is determined by surface pressure of the area where the pushed in cover material is clamped with surfaces of the pulley groove. Accordingly, factors affecting connection strength include, as shown in Fig. 3, the indentation depth, indentation position, shape of the pulley groove edge, etc.⁽¹⁾ It has been confirmed, through testing, that groove edge shape in particular contributes highly. In vehicle durability tests, when the pulley edge shape is maintained as a sharp corner, there is cracking in the direction shown in Fig. 4. In contrast, when the edge is

given an arc shape with certain amount of radius, the cracking does not occur. With this shape, no matter what the spin form process, the cover side shape that corresponds to the pulley part after forming follows the pulley shape and creates a tightly connected shape. Results of durability tests in a vehicle show a relationship between the force with which the pulley clamps the belt and the product lifespan. These results are shown in Fig. 5. From these results it was learned that a small rounding of the pulley edge leads to the fatigue life growing by tens of times.

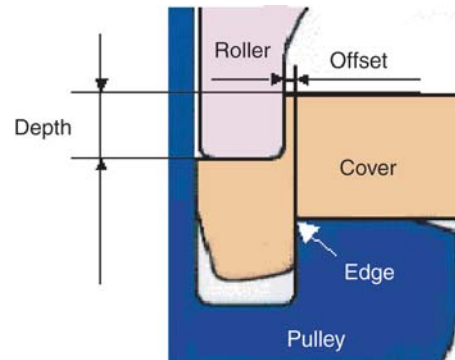


Fig. 3 CVT pulley cover forming



Fig. 4 Section of pulley crack

By showing that this small difference in shape is a major direct contributor to spin forming strength, it is possible to secure spin form strength beyond the constant level, and achieve a stable connection.

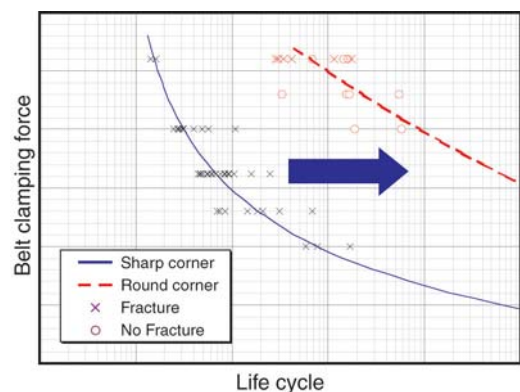


Fig. 5 Loading condition

3. Analysis of Damage Mechanism

3.1. The Effect of Stress Concentration Factor

At the cover edge part, which is the point of origin of pulley cover damage, there is a stress load from the metal belt to the pulley V surface, which causes repetitive bend stress to occur. The difference in sharp corner and slightly rounded shapes in the pulley cover edge that received this sort of repetitive bending is the major factor affecting connection strength. It is thought to be due to differences in stress concentration in the edge area.

In order to clarify the effect of the small arc shape on material fatigue, test pieces made of rolled steel plate, the same material as the cover, were created by grinding, with different radius edges on a V-shaped notch groove, and the fatigue limit of plane bending was measured, under constant minimum stress. The shape of the test pieces is shown in Fig. 6, and the test results are given in Fig. 7.

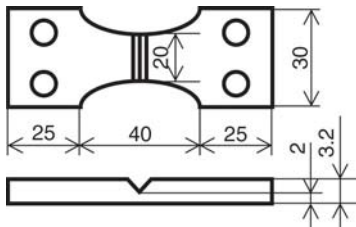


Fig. 6 Fatigue test specimen

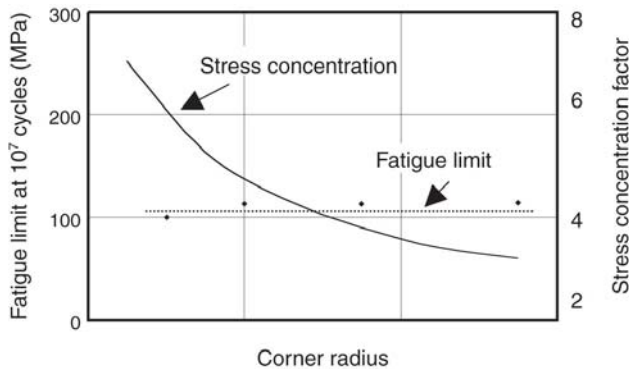


Fig. 7 Relationship between fatigue limit stress and stress concentration factor

From these results, the stress concentration factor of the cover material increases as the arc's radius dimension decreases in the small notched groove, and the material fatigue strength does not change but remains a constant value.

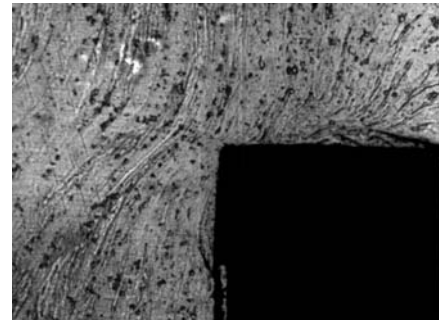
That is to say, the difference in pulley cover durability when the pulley cover edge has a sharp corner and when it is slightly rounded cannot be explained by the stress concentration factor on the edge part.

3.2. The Effect of Plastic Forming Damage on the Spin Forming Part

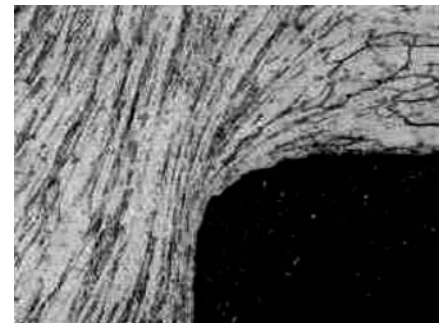
The pulley cover spin forming part is subject to large shear plastic forming in a particular area. At this time, the plastic forming damage to the cover material is thought to

differ according to the edge part's sharp corner shape or small arc shape. An investigation of this forming damage difference was carried out by observing the microstructure of a spin formed part's cross-section. Fig. 8 shows the results of observation at a magnification of 400 times, using an optical microscope.

From these results, it was learned that with a sharp-corner pulley, as shown in Fig. 8-(a), the cover material's fiber flow does not follow the sharp corner shape, and is cut by the edge. In comparison, in the pulley having a rounded shape, as shown in Fig. 8-(b), the fiber flow follows the arc shape. This difference can be clearly seen. When a metal microstructure is pulled in a deformation direction, fiber flow leads to a plant fiber state.



(a) Sharp corner



(b) Round corner

Fig. 8 Microstructure of pulley cover

Although it was learned that there are differences in fiber flow when the edge has a sharp corner and when it is rounded, the effect that fiber flow has on material strength, etc., was not clear.

Therefore, the cover material microstructure was further magnified by 3,000 times, using an SEM (scanning electron microscope). The results are shown in Fig. 9.

From the SEM microstructure observation, as shown in Fig. 9-(a) and (b), both with a sharp corner and a rounded corner, voids can be seen in the shear forming part. It is well known that inclusions occur in plastic forming of the base material, and there is an accumulation of dislocation in the base material's boundary face, and that it grows in the direction of microstructure deformation, that is, the fiber flow direction. Accordingly, as shown in Fig. 9-(a), when the pulley edge part is a sharp corner, fiber flow is cut, and voids appear in the material surface. These voids in the material surface can easily become the point of origin of fatigue failure, just as with micro-cracks.

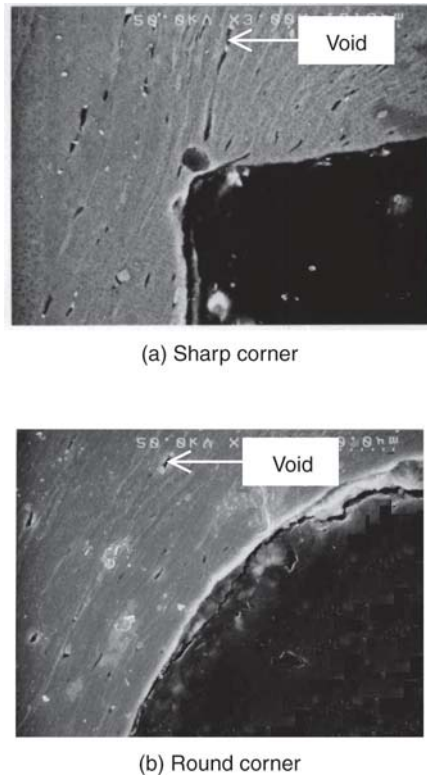


Fig. 9 SEM image microstructure of pulley cover

From this we know the reason why that the connection strength drops for pulley covers having sharp pulley edge corners is because voids generated in spin plastic forming appear in the material surface by the fiber flow cutting. Giving the edge part a rounded shape limits voids in the material surface, and it is possible to improve pulley cover connection strength.

4. Quantitative Evaluation of Forming Damage

The generation of voids around the pulley cover edge is now clear, and it is assumed that the number of voids and their size would affect spin forming durability. Next, quantitative evaluation of this as forming damage was considered.

4.1. The Rupture Theory of Ductile Materials

Generally, ductile fracture has material inclusions, etc, as its point of origin, whereby tiny voids occur, and they gradually grow, finally coming together and causing fracture. In particular, it is important to quantify voids near the surface layer. In this, McClintock's⁽²⁾ equation (1) has been adopted, among the various parts of the theory of rupture.

$$\varepsilon \int \left[\frac{2}{\sqrt{3(1-n)}} \sinh \left\{ \frac{\sqrt{3(1-n)}}{2} \frac{(\sigma_1 + \sigma_3)}{\sigma} \right\} + \frac{(\sigma_3 - \sigma_1)}{\sigma} \right] d\varepsilon = C_3 \quad (1)$$

McClintock's equation expresses damage caused by the generation of voids as stress and plastic strain history, and its special feature is that it can quantify the damage in frequent response to material shear displacement.

4.2. Development of a Forming Simulation Method

The calculation model used to simulate the actual spin forming process, and the deformation diagram, is shown in Fig. 10. Here, the model shows the spin forming stroke applied to the forming roller, and while the work is turned, two support rollers support it. The results of this simulation showed that the forming roller reaction force was the same as that actually measured, so it was judged that the forming process was reproduced. However, because it is a simulation that adopts a finite element method that categorizes, as a solver, according to crash analysis code, or uses a 3D model, to investigate more closely around the pulley cover edge would take a lot of calculation time, and in practical terms is not a good method.

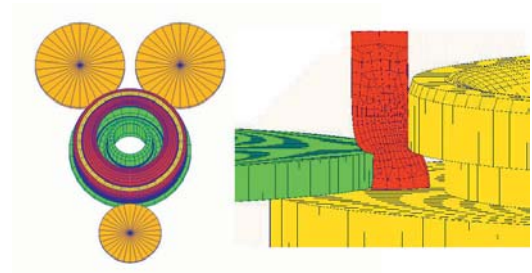


Fig. 10 Forming simulation in 3D

Next, a new forming damage comparison was made between a new 3D model section and a 2D model (Fig. 11) having the same mesh density. Because the results showed that both were quantitatively equal, a detailed analysis of the area around the pulley edge was carried out, using the 2D model.

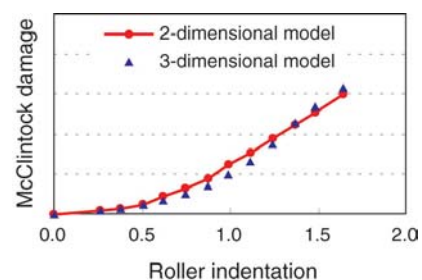


Fig. 11 Comparison of analyses

4.3. The Benefits of Rounding the Pulley Edge

The 2D model deformation diagram used in the investigation into the benefits of rounding the pulley edge, and McClintock damage contour diagram are shown in Fig. 12. The deformation diagram showed good correlation with the section shape of actual spin forming, and so was judged an appropriate result.

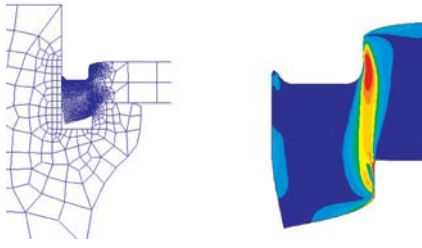


Fig. 12 McClintock damage distribution

Because the damage maximum value was in the same location as the cover cracking point of origin around the edge, the next step was to calculate, in the same way, the damage generated with a number of rounded edge shape radiuses. At that time, indentation depth was taken as a constant value. The results, as shown in Fig. 13, made it clear that there is a sudden increase in damage if the edge rounding radius becomes less than value b. That is to say, pulley cover connection strength in spin forming can be greatly enhanced by rounding the pulley edge.

Furthermore, the relationship between pulley edge rounding dimension and indentation depth is shown in Fig. 14. If the rounding dimension is greater than the value shown as c, even if the indentation depth is great, there is no dramatic increase in the amount of damage.

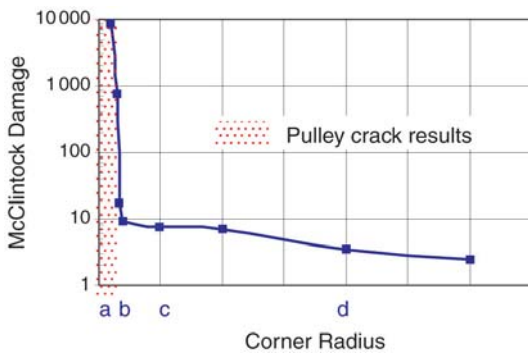


Fig. 13 Damage versus edge radius

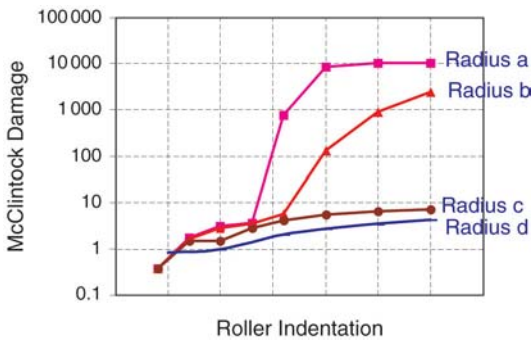


Fig. 14 Damage versus indentation

5. Verification of Durability and Reliability of Connection Strength

Because a drop in pulley cover connection strength actually occurred in a belt reaction force durability test, an investigation was made into how forming damage and stress change while driving.

5.1. Durability Simulation

In the durability test, the metal belt is wrapped around the spin formed pulley, and the vehicle is driven by a fixed speed ratio, belt clamping force, and revolution speed. At this time, belt reaction force is applied to roughly half of the pulley, so it is necessary to carry out analysis with a 3D model. As previously determined, 2D forming simulation results can be developed as 3D results, and so belt reaction force was applied statically. For the belt reaction force, results from a previously reported⁽³⁾ metal belt behavior and stress simulation were used.

Fig. 15 shows the pulley stress contour diagram of the forming process obtained in this way.

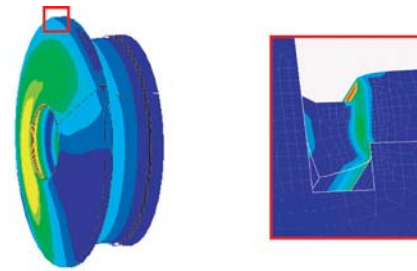


Fig. 15 Pulley stress with belt loading

5.2. Amount of Increase in Damage when Driving

The amount of increase in damage during driving is shown in Fig. 16. From this diagram it can be seen that the amount of damage increase is between 0.1% and 1% at time of forming. This shows that the pulley when driving is used within the material's elastic range, and from the damage point of view, the forming process is dominant.

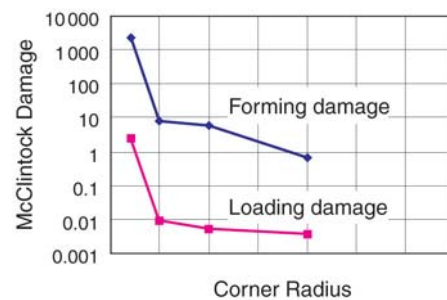


Fig. 16 Damage increment under loading

5.3. The Amount of Increase in Stress when Driving

In verification of connection strength durability and reliability, it is important to know the stress state generated when driving. To this end, as shown in Fig. 17, the simulation was applied under the 3 different belt clamping forces A, B, and C, and the spin forming area's stress increase amount was determined.

As shown in Fig. 18, the shorter the lifespan becomes, the more the stress increases. However, the amount of increase is extremely small – 0.004 to 0.009. This is because the residual stress is maintained as it is, in the plastic range when the spin forming area was formed. Therefore, it is assumed that it is difficult to affect belt reaction force.

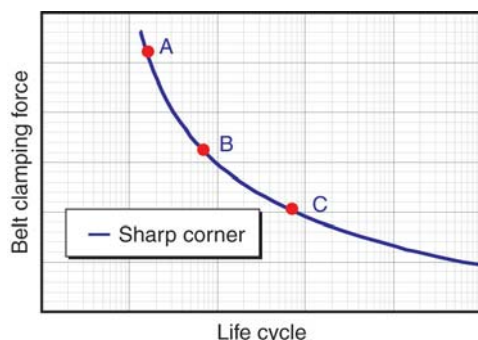


Fig. 17 Three loading conditions

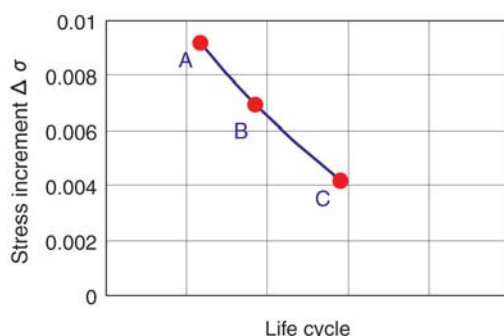


Fig. 18 Stress increment with belt loading

6. Summary

In order to secure a metal belt type CVT pulley cover spin forming connection strength at a constant level or better, the following technologies have been established.

- (1) In fatigue tests of the pulley cover material, using V notched test pieces with small radius, even if the notch edge arc radius falls below the pulley edge radius which leads to critical damage, there is no difference seen in fatigue strength drop.
- (2) In the areas around the pulley cover edge where pulley cover spin forming is carried out, in a state where the material cannot escape, that is to say, in a state nearing hydrostatic pressure, voids are generated.
- (3) When making spin forming connections, if the radius dimension of the rounded pulley edge is below a fixed value, cover side material plastic flow is prevented, void appear in the surface layer, and there is a drop in material strength.
- (4) Through the use of a damage simulation that utilizes the

McClintock equation, a technology was developed to quantify state changes of the pulley cover material originating around the pulley edge.

The cause of pulley connection part cracking is not simple stress concentration, but rather is understood to be due to the fact that material fluidity during machining was not guaranteed to the extent of considering the void generating state. In the future, when carrying out plastic forming that involves large deformation, such as spin forming, it is vital that decisions be made on strength after processing, from the points of view of material, and the damage inflicted.

References

- (1) Japanese Patent Kokai No. (1996) 8-210454: Actuator Case Spin Forming Structure, for a Pulley for Variable Speed Transmission
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