

Development of Metal Pushing V-belt for Continuously Variable Transmission for 2L Class Vehicle

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ABSTRACT

Honda presently mass produces a metal pushing V-belt to enable a compact CVT layout in a 1.5L class vehicle. The project discussed in this paper is based on the technologies developed for mass production of the 1.5L class belt. It furthermore employed dynamic analysis of slack string elements and study of ATF extreme pressure lubricant oil films using measurements of electrical resistance, resulting in the development of a metal pushing V-belt enabling a compact CVT layout in a 2L class vehicle.

The size of CVTs has conventionally been determined by the pitch radius of the V-belt. To increase the torque capacity of the CVT, it was formerly necessary to increase the pitch radius of the belt in order to reduce the belt load. In the newly designed belt reduction of the pitch radius has enabled the distance between the shafts to be reduced, hence reducing the size of the CVT. The newly developed belt achieves a maximum transmitted power of 150 kW with 170 mm between the shafts, and enables a more compact CVT layout.

1. Introduction

The main method of increasing the torque capacity of continuously variable transmissions, using metal pushing belts, is to increase the distance between the shafts of the drive and the driven pulleys. As in other automatic transmissions, the strength is increased by increasing the size of the mechanical elements. Due to the fact that almost no technical reports have been published, which include examples of analyses of the dynamic behavior of metal belts, limits are applied to the maximum rotational speed of the belt to ensure dynamic strength based on empirical observation.

On the basis of the technological knowledge and experience gained in the mass production of a metal belt for a 1.5L class CVT⁽¹⁾⁻⁽⁴⁾, the authors conducted dynamic analyses and studied the properties of the extreme-pressure lubricant oil films (oil film, hereafter) in automatic transmission fluid (ATF) on the various components of metal belts, enabling the development of an original Honda metal pushing belt. This

paper discusses the newly developed technologies employed in the belt.

2. Development Concept

It is necessary to increase the speed ratio range to achieve a balance between improved fuel economy and adequate start torque in a CVT. It is desirable to reduce the pitch radius of the metal belt to ensure the required speed ratio range, but there is a limit to the extent to which the minimum pitch radius can be reduced to ensure that belt fatigue life is maintained. The distance between the shafts must be extended to increase the torque capacity of the CVT, but this results in an increase in the size of the transmission. In addition, the pulley thrust exerted on the metal belt by the pulleys also increases, making the maintenance of an oil film necessary to prevent wear in the sections of the belt making contact with the pulleys.

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Therefore, to increase the torque capacity of the CVT while making the unit more compact it was necessary to employ a belt configuration enabling the belt pitch radius to be minimized, to increase fatigue life by reducing the load on the elements and rings, and to design the belt with consideration of the characteristics of the oil film in each section.

Figure 1 shows a diagram of alternative designs for increasing the torque capacity of the CVT which have identical speed ratio ranges. As the diagram shows, to make the CVT more compact, it is necessary to reduce the distance between the shafts. However, the pitch radius is reduced as a result, and this makes ensuring the fatigue strength of the rings in the metal belt an issue.

Figure 2 shows a plot of maximum transmitted power against distance between shafts for an existing CVT. This graph shows that maximum transmitted power increases with increasing distance between the shafts, increasing the size of the CVT. The issue, therefore, is to reduce the distance between the shafts.

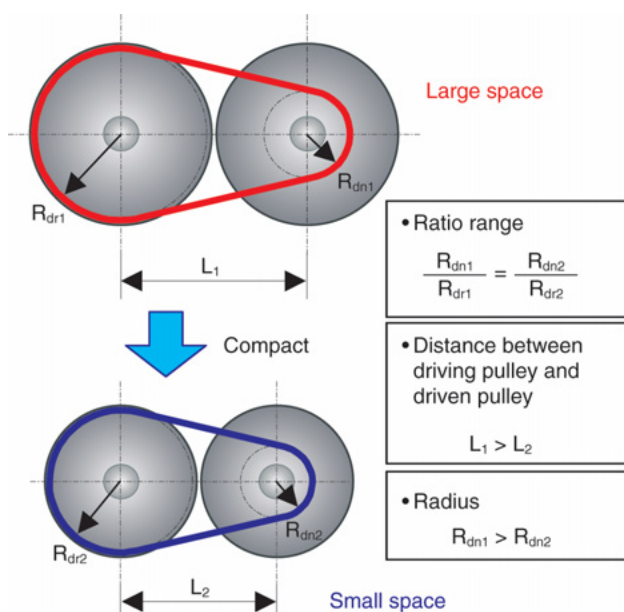


Fig. 1 Structure of CVT with same ratio range

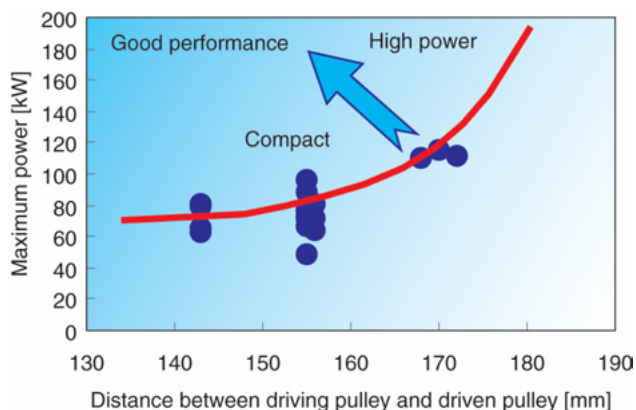


Fig. 2 Maximum power and distance between driving pulley and driven pulley

The following development concept was established on the basis of the above considerations:

- (1) Clarification of the dynamic load on each component of the belt through study of the dynamic behavior of the slack strings of the belt.
- (2) Optimization of the shape of each component of the belt with consideration of dynamic load.
- (3) Guarantee of safety factor through clarification of element fatigue limit load.
- (4) Ensuring of wear resistance by verifying the condition of the oil film on each component of the belt.
- (5) Reduction of cost through employment of new production process.

3. Structure of Metal Pushing Belt

3.1. Structure of Metal Pushing V-Belt and Component Nomenclature

Metal pushing V-belts are composed of several hundred elements and two rows of multiple layered rings (Fig. 3).

Figure 4 shows the nomenclature applied to each component of the belt.

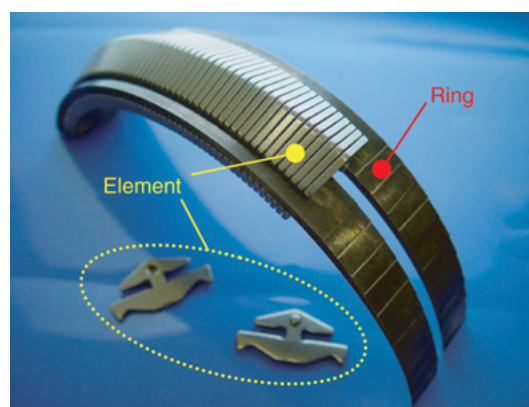


Fig. 3 Metal pushing V-belt

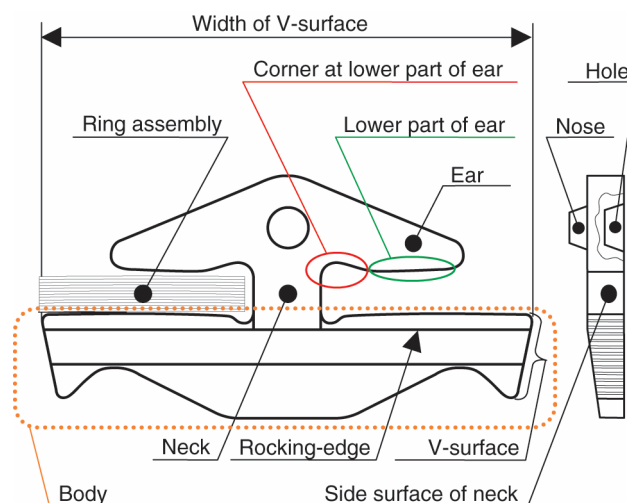


Fig. 4 Configuration of elements and ring assembly

4. Optimization of Element Shape

4.1. Element and Pulley

Measurement of the actual forces of the slack strings in the belt has to the present been considered difficult, but dynamic analyses were conducted in this study to clarify the forces acting on the belt.

4.1.1. Dynamic analysis of elements near exit of driven pulley

Figures 5 and 6 show the results of dynamic analysis of the belt.

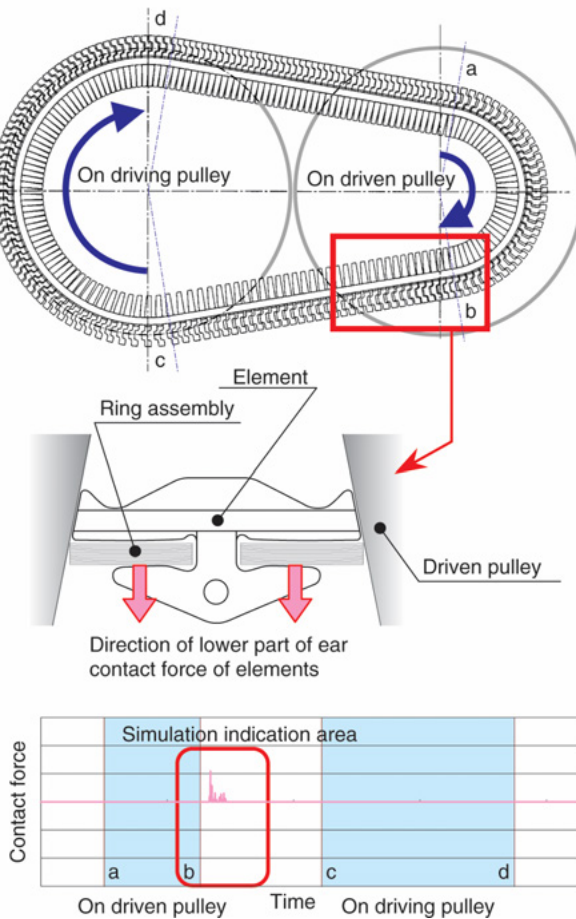


Fig. 5 Lower part of ear contact force of elements

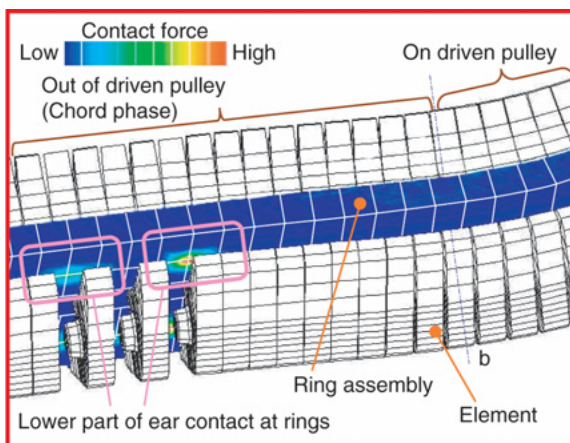


Fig. 6 Lower part of ear contact force of rings

In Fig. 5, entrance to and exit from the driven pulley are marked a and b respectively, and entrance to and exit from the driving pulley are marked c and d respectively. The slack strings correspond to the area between b and c. Figure 5 shows the load on the lower part of the ear. The load is generated as the elements move from the exit of the driven pulley to the slack string section. Figure 6 magnifies the area around the driven pulley exit, and shows the contact between the ring assembly and the lower part of the ear. Contact occurs as the elements proceed from rotary motion to linear motion.

4.1.2. Optimization of shape of sections of the ear

A structural analysis was conducted to determine the stress generated on the element by the load input from the lower part of the ear. This analysis showed that stress was concentrated in the corner of the lower part of the ear. As shown in Fig. 7, by making the corner a compound radius the stress was able to be reduced without increasing the weight of the elements. Figure 8 shows the results of a structural analysis of the load acting on the slack string section of the belt. Modification of the corner of the lower part of the ear from the former simple radius to a compound radius has reduced stress by approximately 40%.

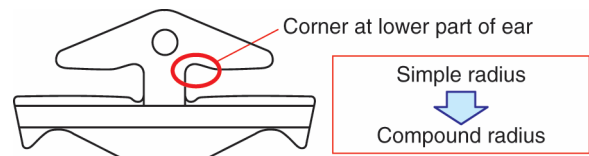


Fig. 7 Configuration at lower part of ear

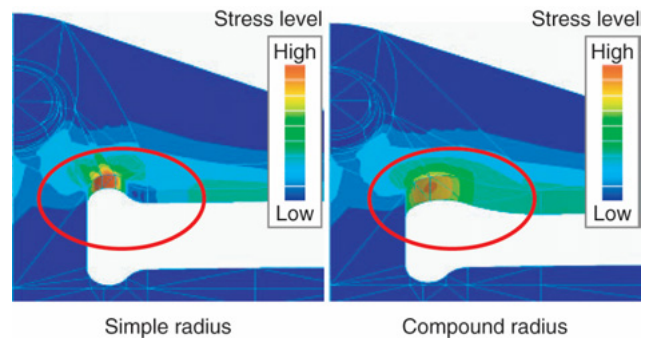


Fig. 8 Corner stresses at lower part of ear

5. Evaluation of Oil Film

The increase of torque capacity to a level appropriate for a 2.0L class CVT required higher wear resistance in the metal belt and pulleys than was required for a 1.5L class CVT. There is an infinitesimal amount of slip between the pulleys and the belt, yet the formation of films by the extreme-pressure lubricants in the ATF ensures wear resistance. It is therefore essential to evaluate the condition of the film. In this study, electrical resistance was used to measure the microscopic slip velocity in an actual belt as a method of evaluating the film. Figure 9 shows a schematic diagram of the circuit used to measure electrical resistance. A pin with a tip of compound radius is pressed onto a test piece corresponding to the pulley or the rings and made to slide. A

fixed voltage is impressed between the pin and the test piece, and the separated voltage which is generated against the resistance between the two surfaces is registered as a film between the surfaces making contact. If no film is formed voltage is recorded as zero, but when a film is formed the voltage reading varies according to the condition of the film.

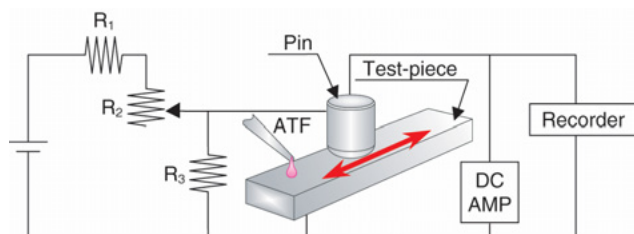


Fig. 9 Circuit for measurement of electrical resistance

5.1. Between the Elements and the Pulley

5.1.1. Relative velocity of elements and pulley

Figure 10 shows a schematic view of measurements of relative slip velocity between the elements and the pulley. A sensor to measure the velocity of the elements and a displacement meter to measure the pitch radius of the metal belt were mounted at the driven pulley to record measurements in a range of angles between 0° and 150° from their position of placement. The relative velocity of the elements and the pulley was determined from the difference between the velocity of the metal belt and the velocity of the pulley at the positions at which the belt wraps around the pulley.

Figure 11 shows the relationship between the wrap angle of the belt on the driven pulley and the pitch radius of the belt at a ratio of 0.5. It is apparent that the pitch radius of the belt decreases between the entrance to and the exit from the driven pulley. Elastic deformation of the elements on the pulley and deformation of the pulley strongly influence this change in the pitch radius of the belt on the driven pulley.

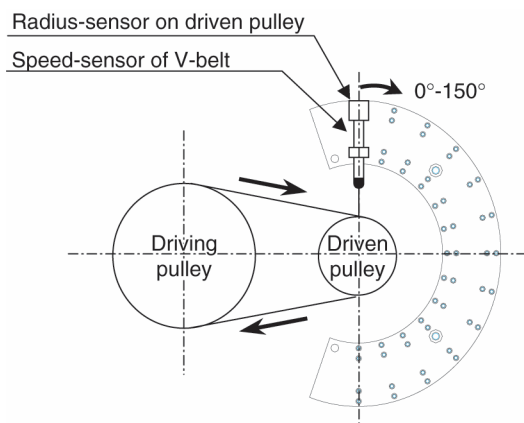


Fig. 10 Schematic view of measurement of sliding velocity on driven pulley

Figure 12 shows the results of calculations of the relative velocity at a tangential direction between the elements and the pulley. The relative slip velocity between the elements and the pulley is approximately zero at the entrance to the

driven pulley, then steadily increases between the entrance and the exit, and is at its maximum at the exit from the pulley. This maximum relative slip velocity was used as the relative velocity for evaluation in oil film tests.

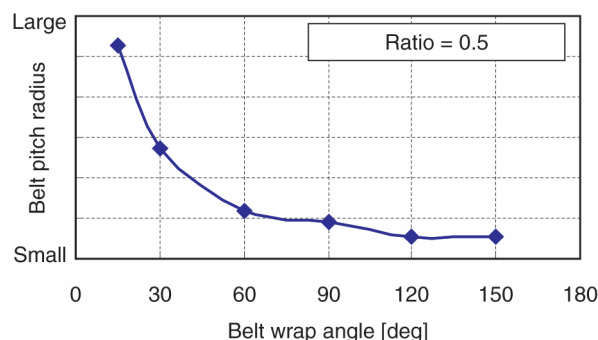


Fig. 11 Variations in belt pitch radius with respect to belt wrap angle

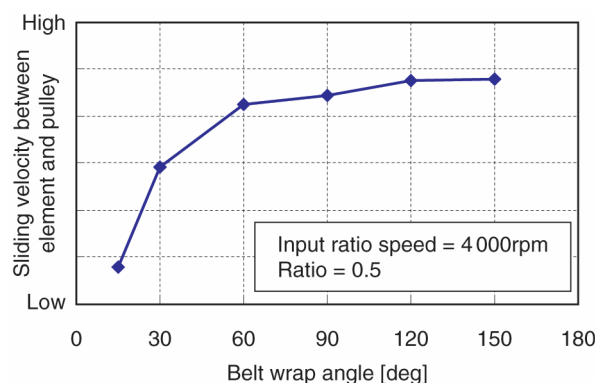


Fig. 12 Sliding velocity with respect to belt wrap angle

5.1.2. Evaluations of oil films formed by different ATF extreme-pressure lubricants

Measurements of electrical resistance were used to determine the conditions of maintenance of different ATF oil films with respect to Hertzian contact pressure and relative velocity between the elements and the pulley in conditions of actual use. A sulfur-phosphorous extreme-pressure lubricant was added in ATF1, while a sulfur extreme-pressure lubricant was added in ATF2. The results of oil film measurements for these two ATFs are shown in Figs. 13 and 14.

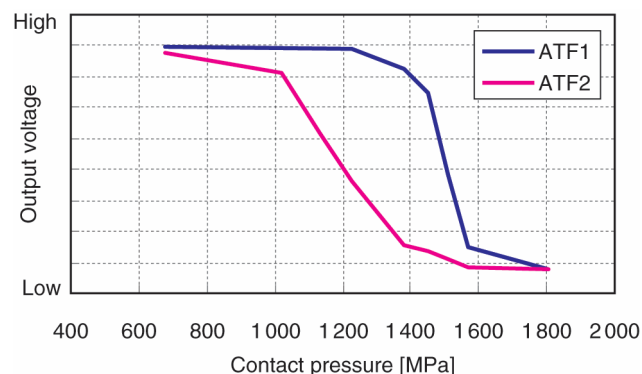


Fig. 13 ATF oil film conditions with respect to contact pressure

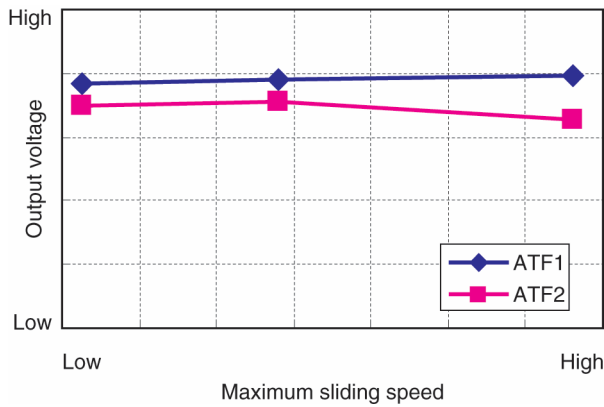


Fig. 14 Relationship between oil film conditions and maximum sliding speed

Figure 13 shows the results of oil film measurements with changes in contact pressure. Both the ATFs maintained stable film characteristics at low and medium contact pressures, but at high contact pressures ATF1 recorded a higher separated voltage as pressure increased; indicating superior maintenance of the film. Figure 14 shows the results of measurements with changes in relative velocity. As relative velocity increases ATF1 maintains fixed characteristics, but ATF2 shows a slight performance decline.

5.2. Elements and Rings

As shown in Fig. 15, a mesh is applied to the inner surface of the rings. The shape of the mesh has an effect on the lubrication performance of the rings.

Figure 16 shows changes in the condition of the oil film with changes in the contact ratio of the mesh. These results demonstrate that a superior oil film is achieved with a lower contact ratio. The shape of the mesh was optimized on this basis.

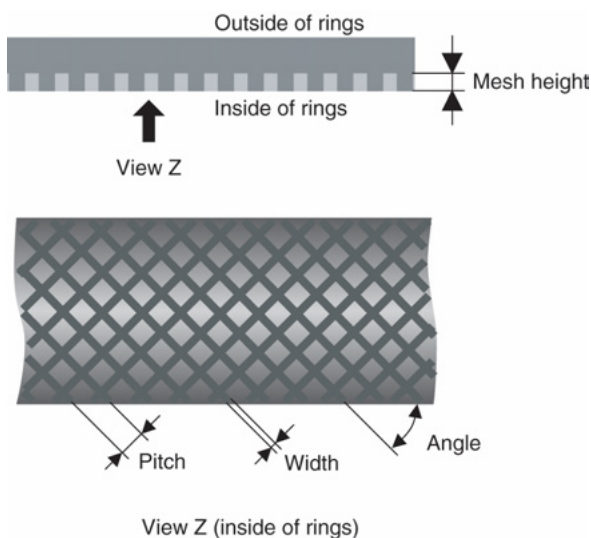


Fig. 15 Configuration of ring mesh

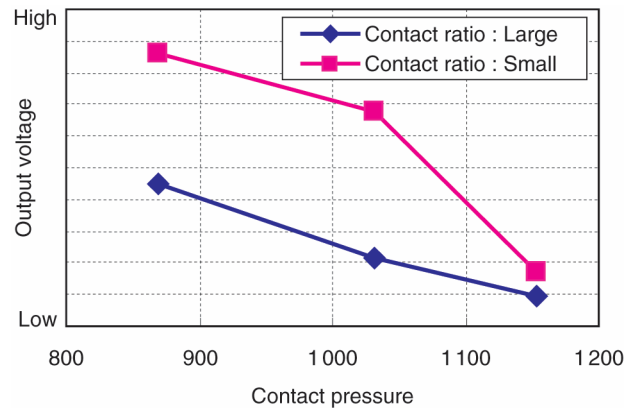


Fig. 16 Oil film conditions at differences of contact ratio

6. Cost Reduction

Increasing the size of the rings should necessarily increase costs, but cost reductions have been achieved by applying a new method to produce the ring edge.

6.1. Method of Polishing Ring Edge

The rounded form shown in Fig. 17 is desirable for the ring edge to reduce the load generated when the side of the element neck makes contact with the pulley V-surface.

The ring edge was previously formed by using a grindstone to cut a drum-shaped cylinder of metal into rings of a set size and then barrel polishing the rings, as shown in Fig. 18. The increased diameter of the rings required in a metal pushing V-belt for a 2L class CVT would lengthen the time required for processing, hence increasing costs.

A new manufacturing method using a plastic brush treated with abrasive powder was therefore developed to reduce the time required for manufacturing.

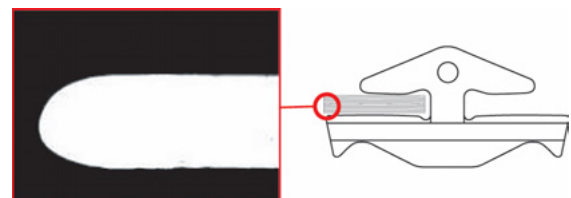


Fig. 17 Profile of ring edge

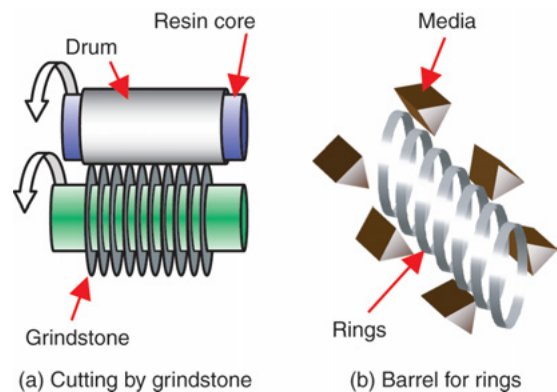


Fig. 18 Manufacturing method of former rings

Figure 19 shows a diagram of the new method employing the brush. After cutting, the rings are clamped to a turntable which rotates automatically. The brush, attached to a brush head, also rotates, polishing the ring edges. This new manufacturing method has significantly reduced costs over the previous method.

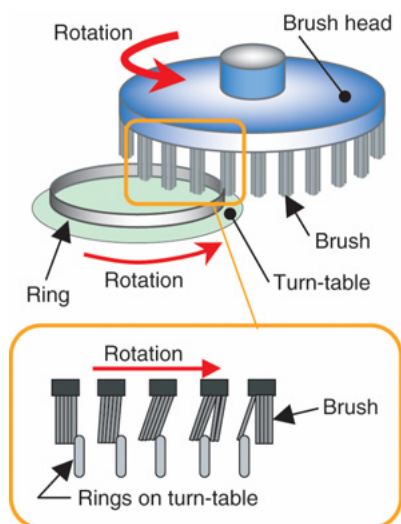


Fig. 19 Ring edge brushing method

7. Verification of Fatigue Strength

7.1. Elements

7.1.1. Element ear

Unit damage tests and damage tests in a functioning CVT were carried out on the element ears to verify the results of the dynamic analysis of the elements. These tests demonstrated the effectiveness of the compound radius shape.

Figure 20 shows the form and fracture face of a fracture occurring in an element during durability test in a functioning CVT. The fracture can be judged as occurring due to forces input from the lower part of the ear, which corresponds well with the results of dynamic analyses.

Figure 21 shows the results of unit strength tests for the element ears. The arrows in the figure represent elements in which no fracture occurred during the cycle concerned. The tests confirmed the greater strength of the compound radius shape than the simple radius shape, and verified that they demonstrated the required safety factor with respect to the loads occurring in a functioning CVT.

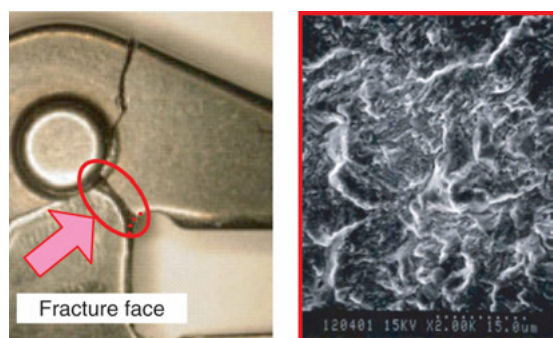


Fig. 20 Damaged element and SEM photograph of fracture face

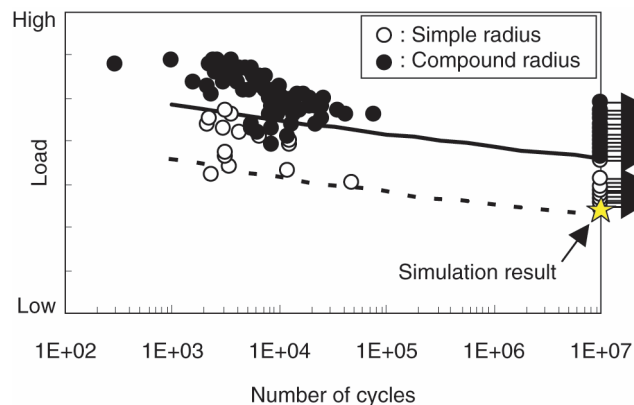


Fig. 21 Comparison of fatigue behavior in simple radius element and compound radius element

7.1.2. Giga-cycle fatigue strength of element materials⁽⁵⁾

To the present, unit strength tests on elements have not been conducted past 10^7 cycles on the premise that a fatigue limit exists. Ultrasonic fatigue tests were conducted on element materials to verify the existence of this fatigue limit. Figure 22 shows the results of giga-cycle fatigue tests. In these tests the element material did not fracture from inclusions at high cycles, but fractures always originated at the surface. These results verified the existence of a fatigue limit for the element materials. Figure 23 shows an outline of the equipment employed in the ultrasonic fatigue tests. A piezo electric element is used as the excitation source, and the test piece resonates as the amplitude of vibration is increased.

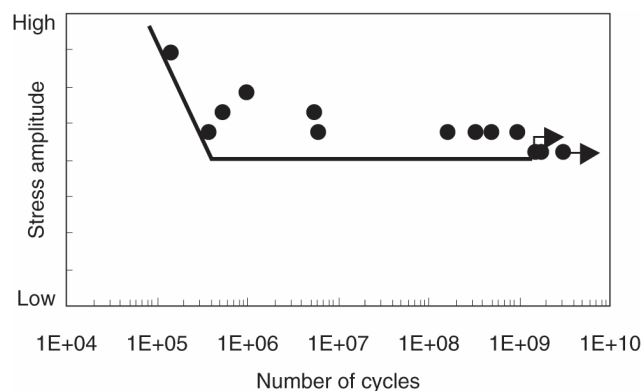


Fig. 22 S-N diagram by ultrasonic fatigue test

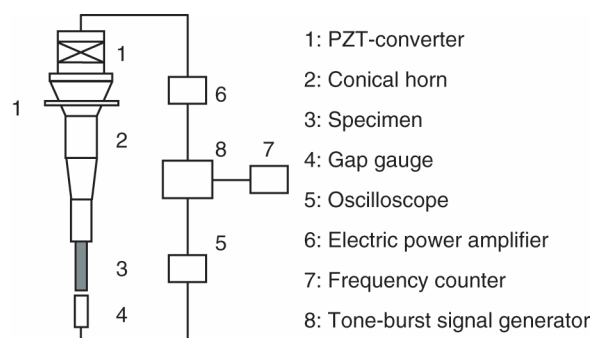


Fig. 23 Block diagram of ultrasonic fatigue test

7.2. Ring

Ring fatigue tests were conducted to determine whether the new manufacturing method for the ring edges had any effect on durability.

Figure 24 shows the results of unit fatigue tests on the rings. The results show that there is no difference in strength between rings produced using the previous method and the new method.

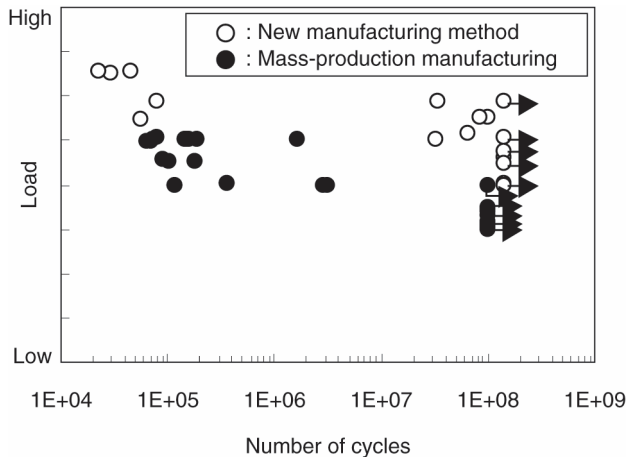


Fig. 24 Comparison of fatigue behavior in rings produced by mass production method and new manufacturing method

8. Maximum Transmitted Power

The reduced minimum pitch distance of the belt resulting from the reduction of the distance between the shafts necessitated high durability in the metal pushing belt. Figure 25 shows the maximum transmitted power of the CVT based on the results of durability tests. The development project conducted for the 2L class CVT metal pushing belt has succeeded in increasing the power of the CVT while making the unit more compact.

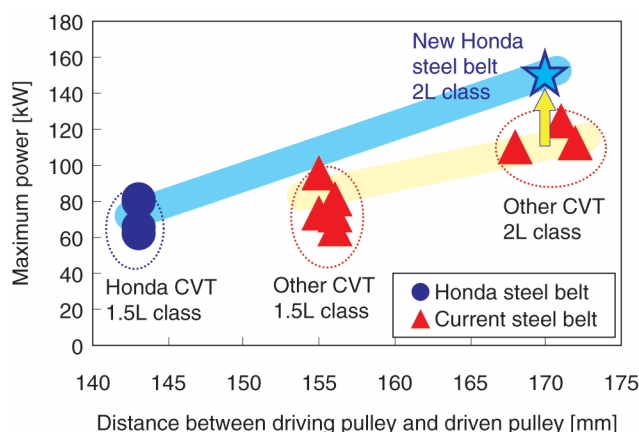


Fig. 25 Potential of newly developed V-belt

9. Conclusion

The following are the most significant details of the development project for a 2.0L class CVT metal pushing V-belt:

(1) Dynamic analysis of the metal pushing V-belt showed

that the contact between the lower section of the element ear and the laminated rings at the exit of the driven pulley generates significant stress on the corner of the lower section of the ear.

- (2) Application of a compound radius shape for the corner of the lower section of the element ear reduced the stress on the ear with no increase in weight.
- (3) Tests showed that at high cycles inclusions in the element material did not affect the durability of the element, and confirmed the existence of a fatigue limit.
- (4) Evaluation of ATF extreme-pressure oil films using measurements of electrical resistance clarified the effect of differences in the composition of the ATF fluid and the mesh ratio, and enabled the optimization of the form of the mesh.
- (5) The employment of a new manufacturing method which uses a plastic brush treated with abrasive powder to form the edges of the rings has enabled production costs to be reduced while maintaining an equivalent level of strength and durability to that of rings produced by the previous method.

Items (1)-(5) above have enabled the minimum pitch radius of the metal belt to be reduced; thus, increasing the compactness of the CVT. In the future the authors wish to pursue further evolutions with more theoretical investigation of the forms of the components of the belts and the development of groundbreaking manufacturing technologies.

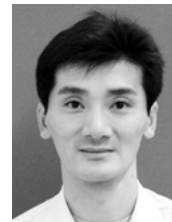
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