Clutch texture technology inspired by two types of creatures: From conception to design to mass production method

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Summary

JATCO has improved clutch friction stability and extended clutch service life by machining a texture on the mating steel plate instead of on the conventional friction material. This texture was inspired by two creatures to address stick-slip that is a fundamental issue of clutches. This article describes the new engineering method from the perspectives of conception, design and mass production.

1. Introduction

In order to maintain a habitable global environment for people, there is a greater need than ever before for society to use sustainable things. The automotive industry also has a large responsibility in this regard. Reforms are necessary not only for achieving carbon neutrality but also in various fields, including extending the usable lifetime of vehicles.

Currently, I am engaged in the creation of innovations and the development of fundamental technologies. Being in a position that demands unprecedented technological concepts, I have focused on biomimetrics, i.e., nature-inspired innovation.

Living things have undergone a long history of evolution to reach their present forms since the earth was formed. Learning from and drawing upon that evolution, I believe, can provide approaches for pursuing innovations in the process of studying sustainability. The surface texture technology developed in this project was inspired by two types of creatures.

The hexagonal arrays seen on the feet of katydids and frogs are thought to function for stick-slip control and grip enhancement. Accordingly, a technology was developed for machining a texture of fine hexagonal grooves on the steel plate that is a constituent part of transmission clutches.

As a result, a substantial improvement of clutch friction characteristics was accomplished as a benefit gained from nature. This article describes the details of this development from conception to the establishment of a mass production method.

2. Conception and selection of part for application

2.1 Conception

Information on nature was researched focusing on inspiration from outside the automotive industry in seeking concepts for unprecedented technologies. Borrowing the wisdom of creatures that have accumulated a long evolutionary history was assumed to be the most suitable approach to finding things that vastly exceed the realm of human thought.

A search was made for information especially related to insects in the natural world. The shells of insects seemed to be like a robot in having simplicity combined with complexity. This gave the impression that much can be learned from them, making it easier to come up with ideas applicable to industrial products.

In the course of investigating insects and technologies and other ideas derived from them, I came across the genre called biomimetrics. I found that extremely interesting studies are under way in a variety of fields, including robots based on the ecosystem of ants, the brains of flies and the feet of sea lice. Among these studies, there was an

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article about the bottom of katydid feet.

The bottom of katydid feet has a hexagonal texture that has an expected value of stick-slip control. The results of friction experiments conducted using a silicone material showed that stick-slip was eliminated, yielding smooth friction characteristics (Fig. 1).[(1)-(2)]

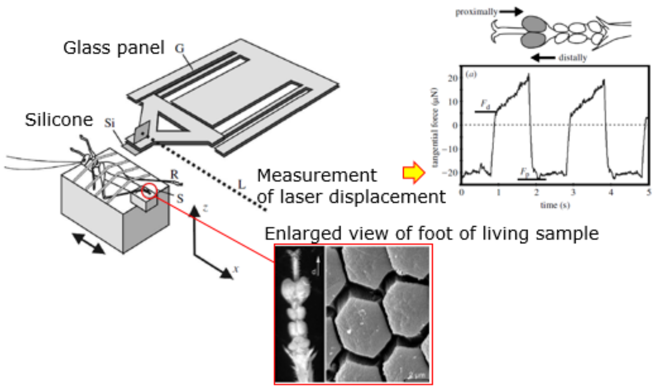

Fig. 1 Information extract for the bottom of katydid feet

Further research was then conducted on the bottom of creatures' feet. A close examination of grasshoppers, which give the impression of being similar to katydids, revealed that they apparently did not have any hexagonal pattern on the bottom of their feet. This suggested that grasshoppers flee by flying away while katydids flee by running away.

A close examination of frogs, which, like katydids, jump on their hind legs, revealed a hexagonal structure on their feet. Frogs have been researched in the medical field. Reports have mainly been written about the function of this structure for improving gripping ability (Fig. 2).[(3)]

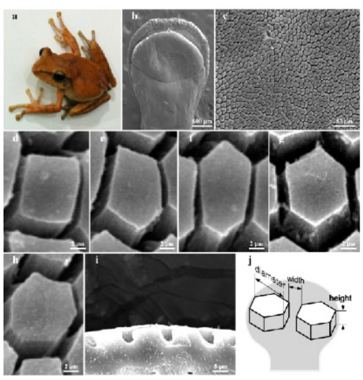

Fig. 2 Information extract for the bottom of frog feet

One point of interest here is that both types of creatures, an insect and an amphibian, have a hexagonal pattern on the bottom of their feet, though they are different species and also live in different environments. Another point is that the function of the pattern of each one is different. It was inferred that the hexagonal pattern imparts multiple positive effects on frictional surfaces, so it was decided to investigate this texture.

2.2 Applied

2.2.1 To which part should the texture be applied?

The question of to which transmission parts the texture should be applied in order to use it effectively for our products was also an extremely important point for increasing the likelihood of obtaining the desired effect.

Frictional surfaces are found at a variety of places inside a transmission, including the shafts, belt, pulleys, gear surfaces and clutches, among other locations. It was concluded that clutch parts were suitable locations where the functionality of the hexagonal pattern was desired (Fig. 3).

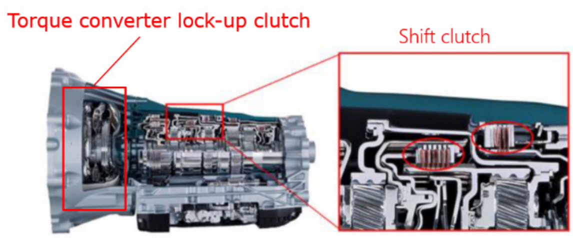

Fig. 3 Candidate parts for texture adaptation

Why are clutches suitable? Clutches engage and disengage repeatedly in the process of shifting gears. Clutches are engaged by gradually applying pressing force to achieve engagement. A slipping state occurs during the transition. When there is slipping, stick-slip can occur as a natural phenomenon at frictional surfaces. Stick-slip is an issue because it causes vehicle occupants to feel an unpleasant vibration.

Clutch friction is usually under design control, so the likelihood of stick-slip occurring is very small. However, stick-slip can occur accompanying deterioration with use.

Since katydids suppress stick-slip in nature, it was decided it would be worthwhile to attempt a similar application to the stick-slip phenomenon in JATCO's transmissions. Moreover, it was expected that it would also improve gripping force as noted earlier for frogs.

Clutches are engaged by friction to transmit driving force, and energy is also required during engagement. An increase in gripping force would result in a higher friction coefficient, and it could be expected that pressing force would also be reduced.

2.2.2 To which clutch parts should the texture be applied?

The clutch friction material and steel plate were considered as two conceivable places for applying the texture. In this study, the steel plate surface was selected. In a conventional sense, there was concern that machining the texture on the steel plate would produce a file-like effect that would abrade the cellulose and other components of the friction material. However, considering that the two types of creatures live on the tops of leaves containing cellulose, it was envisioned that the texture might be viable if the surface pressure was reduced to the level occurring in nature (Fig. 4).

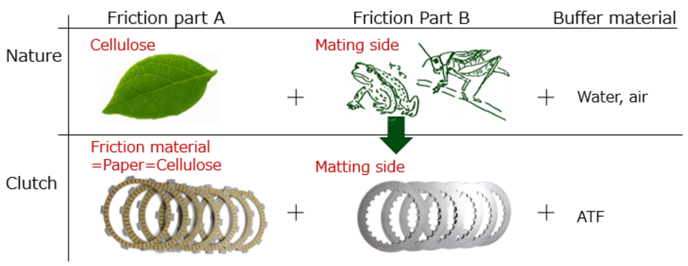

Fig. 4 Conceptual representations of adaptation locations

3. Design

3.1 Calculation of surface pressure

The detailed dimensions were calculated by making a Fermi estimate. Taking into account all the aspects up to mass production, it would be virtually impossible to calculate everything because there are so many points that differ from the living environment of the two types of creatures, including clutch immersion in oil and the stiffness of steel, among other things. As the development concept, it was decided to use the approximate surface pressure that the creatures would experience in their natural environment on the earth (Fig. 5).

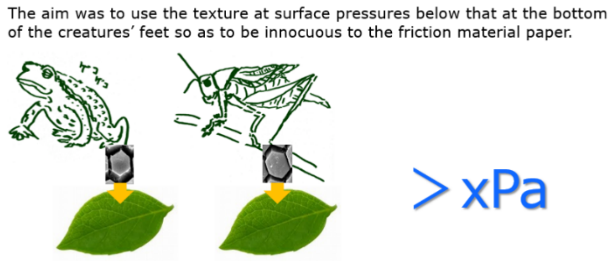

Fig. 5 Representation of concept

There are blogs on the Internet by people who like insects, so it was possible to find some information about the mass of katydids. The testes of katydids account for about 1-13.8% of the mass and weigh about 2.7-70.1 mg. From these data, the body weight was calculated to be 491.9 mg.

A technical paper[3] concerning research on katydids contained image data for the bottom of their feet. The area of the hexagons was measured and provisionally assumed to be $1.67576 \times 10^{-11} m^2$. The size of one foot was deduced from the overall length and the number hexagons was estimated for one foot (Fig. 6).

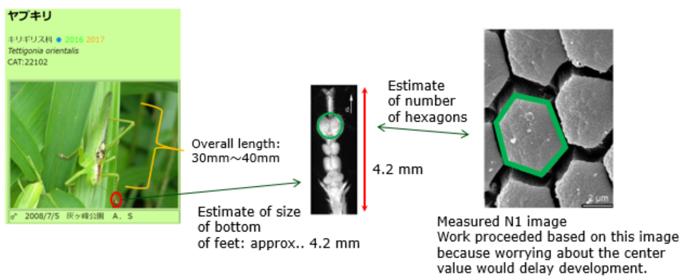

Fig. 6 Enlarged view of the bottom of katydid feet

Next, it was decided to calculate the total number of the hexagons that do the functional work. While katydids have six legs, it was hypothesized that their center of gravity is probably concentrated on the two thick rear legs when they move, not when they are stationary. Under that assumption, the surface pressure concentrated on their rear feet was calculated in this study. Based on this information, it was hypothesized that there were approximately 70,000 hexagons on the bottom of the feet supporting the body weight. The surface pressure on one hexagon was then determined as an index.

A similar investigation was also conducted for frogs. Because the order of magnitude was similar for both the hexagon size and surface pressure, it was decided to use the calculated results for katydids.

3.2 Resizing the hexagons for application to automotive parts

A study was conducted regarding the application of the texture to transmission clutches, based on the surface pressure of the single-plate lock-up clutch of a torque converter, which experiences high surface pressure. The hexagons of the creatures were expanded in size to match the lock-up clutch design, resulting in hexagons that measured approximately 120 μm on one side.

3.3 Design of groove width and depth

The groove width and depth were set at 50 μm and 20 μm, respectively. Because the dimensions could not be measured from photographs of the creatures' feet, they were provisionally determined from the oil film thickness and a margin allowing the transmission fluid to flow through the grooves easily. The dimensions were comprehensively determined taking into account prototyping and mass production methods and in reference to cost and other factors.

3.4 Orientation of hexagons

A technical paper(5) concerning research on frog legs stated that fluid flow differed depending on the orientation of the hexagons as to whether the corners or sides pointed forward. Hexagons with corners pointed forward were referred to as corner-sliding (CS) and those with sides pointed forward as side-sliding (SS). Those designations are used in this article.

In addition, the adaptation of micro-grooves on the clutch plate was also expected to have the effect of improving micro-cooling by the transmission fluid flowing through the grooves. However, because clutches are rotating parts, the positioning of regular hexagons without any modification would cause their orientation to differ at the 12 and 6 o'clock positions and at the 3 and 9 o'clock positions. It was thought that the effects of rotation on the state of the fluid and frictional surface might differ at each position. Therefore, the angles of the hexagons were slightly varied radially, and the hexagons were positioned so that their orientation would be identical in relation to the direction of rotation (Fig. 7).

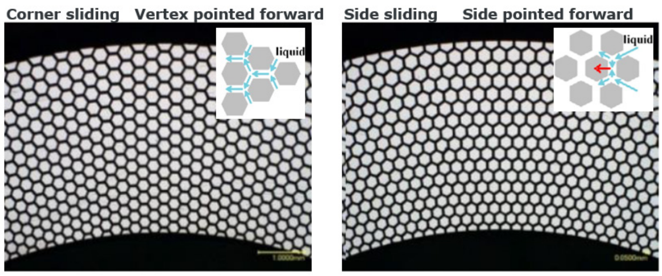

Fig. 7 Prototype test pieces directionally aligned (Left: CS; right: SS)

4. Investigation results

4.1 Prototyping

First, a femtosecond laser was used to machine an initial prototype of the texture. In order not to attack the friction material, the texture had to be machined precisely while suppressing swelling due to the heat-affected zone (HAZ). The selection of this machining technique achieved the intended texture (Fig. 8).

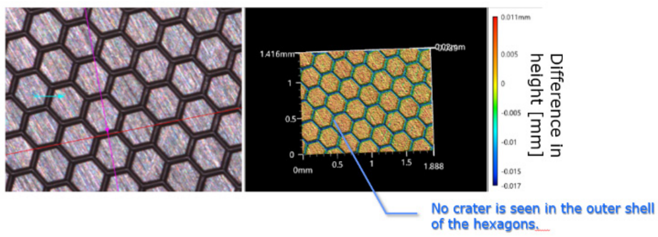

Fig. 8 Appearance of texture prototype

4.2.1 Result: effect on improving the coefficient of friction (μ)

The μ-V characteristic is a performance index obtained by plotting μ on the vertical axis in relation to differential rotation, i.e., sliding velocity, on the horizontal axis.

A characteristic that trends downward to the right is referred to as a negative gradient, which is a factor causing stick-slip. A clutch with a negative gradient tendency was prepared, and it was confirmed that replacing the steel plate with a textured plate obtained a characteristic with a positive gradient. Robustness against the fluid temperature and surface pressure was also improved, and performance stabilized under conditions of a low temperature and low surface pressure where a negative gradient tends to appear. Figure 9 shows the characteristics obtained at 40°C and 0.2 MPa.

Because the measured results did not show any large difference between the CS and SS orientations, the following discussion focuses on the CS orientation.

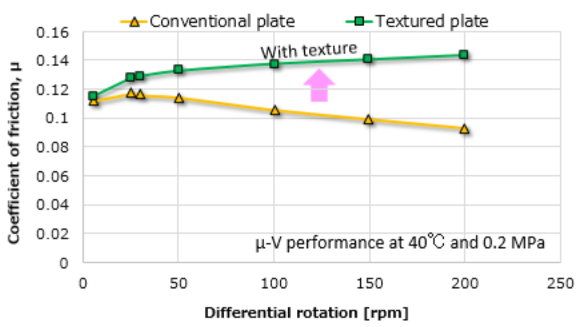

Fig. 9 μ-V performance

4.2.2 Result: Durability lifetime until reaching a negative μ gradient

Durability tests were conducted using a low-velocity friction apparatus (LVFA) for measuring clutch service life. The temperature of the test transmission fluid was adjusted to 120°C, and friction characteristics were measured at 40°C, 80°C and 120°C at certain specified intervals. Compared with clutches with ordinary steel plates, it was found that clutches with a textured steel plate extended by 65% the time until the μ-V characteristic showed a negative gradient and fell below the performance criterion. The lifetime extension was especially prominent under a low surface pressure condition (Fig. 10).

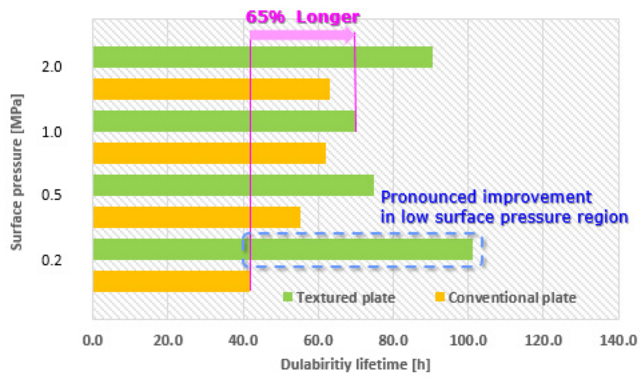

Fig. 10 Difference in service life due to the effect of the texture

4.2.3 Consideration

The foregoing results were due to the functionality and benefits imparted by the texture, which ordinary steel plates have not possessed. It is assumed that the following factors were effective in improving friction characteristics and extending clutch service lifetime:

A) the hexagonal pads stabilized the μ characteristic in the region of high differential rotation;

B) the grooves stabilized the μ characteristic in the region of a low temperature and low surface pressure by helping to optimize the fluid film on the frictional surface;

C) moreover, the transmission fluid in the grooves enhanced cooling performance,

which had the effect of improving friction characteristics and extending durability lifetime.

5. Toward mass production

Forming grooves of 50 μm in width and 20 μm in depth on steel plates having even larger undulations requires considerable technical skill. Production scale and production speed are also critical elements in adopting the texture on automotive parts. A survey was conducted at the planning stage concerning manufacturers possessing both the requisite technical capabilities and production scale. A company with precision press processing technology was found in Japan. Following prototype validation, a prototype die was fabricated at that company and press processing trials were launched. Development work is still under way at present, including a review of the press processing conditions while making repeated improvements.

The smooth progress of trials of the mass production method enabled other studies to be undertaken ahead of schedule that were not limited to single-part experiments and included confirmation of in-vehicle process control and an examination of process variation.

6. Conclusion

(1) The stability of clutch friction characteristics was markedly improved by applying a surface texture inspired by two types of creatures. It is expected that adaptation to low-temperature conditions in particular will contribute to use on electric vehicles that have little waste heat following vehicle start-up. It is believed that this surface texture technology can contribute to new ways of using vehicles, including lengthening their usable lifetime.

(2) It is difficult to create a motif when applying properties of creatures to industrial products. The simple hexagonal structure on the bottom of the creatures' feet enabled a design based on Fermi estimates, making it possible to obtain the intended functionality.

7. References

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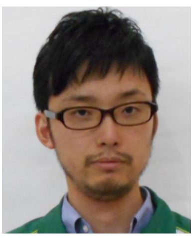
■ Author ■



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