

Research on Silent Chain Elongation Mechanism and Prediction

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ABSTRACT

The silent chain elongation mechanism due to soot in the engine oil was analyzed and the relationship between chain elongation factors and the chain elongation rate was obtained through experiments in order to construct technology for predicting silent chain elongation.

The results showed that almost no silent chain elongation occurred when there was no soot in the engine oil. However, when soot is present on the pin and plate sliding surfaces, three-body abrasive wear produces plate wear, which increases chain elongation. In addition, experimentally deriving a silent chain elongation predictive formula from the relationship between chain elongation factors and the chain elongation rate enabled estimation of silent chain elongation from the initial design stages.

1. Introduction

Chain-driven systems are more durable and compact than belt-driven systems, so chain-driven systems are often used in the cam-driven systems of engines. In addition, silent chains have come to be used as they are quieter than roller chains. When using a chain-driven system, chain elongation influences the valve timing, chain behavior and other factors. Therefore, design should take into account chain elongation in the actual operating environment to help assure engine reliability and product appeal. However, various factors are associated with chain elongation, which makes it a challenge to predict chain elongation in the actual operating environment from the initial design stages.

A number of studies have been reported on simulation of chain tension, noise, friction and other factors in chain-driven systems⁽¹⁾⁻⁽³⁾. However, the chain elongation mechanism has not yet been clarified, so prediction using simulations is a challenge, and there are few reports of technology for predicting chain elongation.

Silent chain elongation occurs when the plate holes and pins become worn due to sliding between the pins and plates when the chain meshes with the sprockets and bends. Therefore, the engine operating status, oil supply status and other factors when the chain bends must be taken into account to predict chain elongation.

On the other hand, soot in the engine oil is known to

influence the wear of engine sliding parts. Pin and plate sliding surface wear is also a potential cause of silent chain elongation, so soot in the engine oil is thought to influence silent chain elongation. This means that the chain elongation mechanism due to soot in the engine oil must be clarified to predict silent chain elongation.

Therefore, this study used experimental results to clarify the chain elongation mechanism due to soot in the engine oil. In addition, a chain elongation predictive formula was experimentally derived by analyzing the relationship between chain elongation factors and the chain elongation rate. This enabled prediction of silent chain elongation.

2. Silent Chain Elongation Mechanism

2.1. Elongation Due to Soot in the Engine Oil

Engine bench tests were performed to confirm the effect of the soot concentration in the engine oil on silent chain (hereafter, “chain”) elongation. In these tests, carbon black was mixed into the engine oil in place of soot, and the engine was operated at the constant speed of 5000 rpm with different carbon black concentrations. Table 1 shows the specifications of the engine used in the tests and the test conditions. In addition, Fig. 1 shows the chain composition, Fig. 2 shows the chain elongation measurement results, and Fig. 3 shows the pin and plate wear amounts. Figure 2 shows that almost no chain elongation occurred under

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Table 1 Engine specifications and test conditions

Cylinder configuration	Inline 4
Bore × Stroke (mm)	87.0 × 99.0
Displacement (cm ³)	2354
Compression ratio	10.5
Chain type	Silent chain
Chain pitch (mm)	6.35
Number of link plates	4/3
Number of links	176
Engine speed (rpm)	5000
Engine oil	ILSAC GF-4, 5W-20
Soot concentration (wt%)	0, 0.4, 1.0

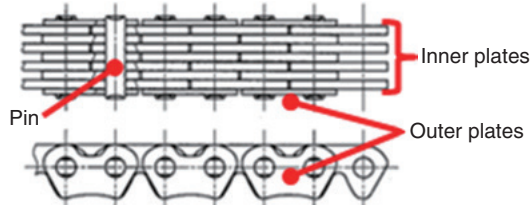


Fig. 1 Composition of silent chain

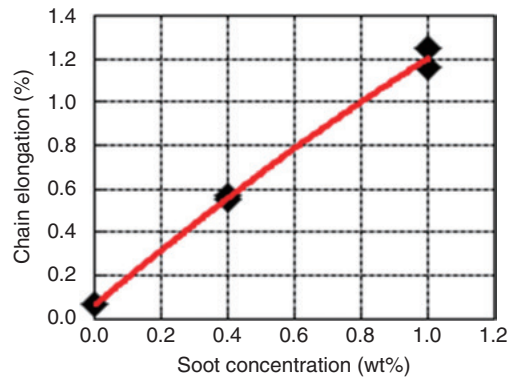


Fig. 2 Influence of soot concentration on chain elongation

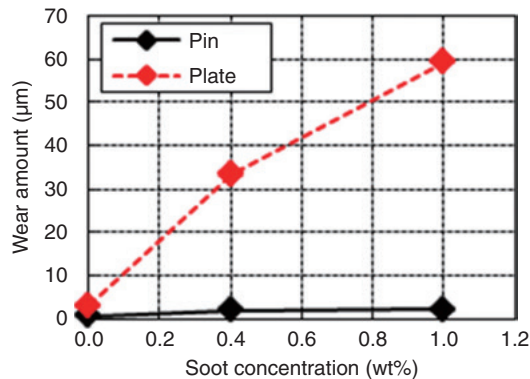


Fig. 3 Wear amount of pin and plate

Table 2 Chain specifications and test conditions

Chain type	Silent chain
Chain pitch (mm)	6.35
Number of link plates	4/3
Number of links	102
Load (N)	1500
Oil supply (l/min)	0.1, 1.0
Soot concentration (wt%)	0, 1.0

conditions of a carbon black concentration of 0 wt%. In addition, within the concentration range confirmed in these tests, chain elongation increased together with the concentration. These results indicate that chain elongation occurs when soot is present in the engine oil, and that the chain elongation rate is influenced by the soot concentration in the engine oil.

Next, Fig. 3 shows that the pin wear amount did not change much and there was also little wear as the carbon black concentration was increased. In contrast, the plate wear amount increased together with the carbon black concentration. The chain pins are surface-treated to a hardness equal to or greater than that of soot, but the plate hardness is lower than that of soot. Abrasive wear is known to generally be inversely proportional to hardness. These test results show that almost no chain elongation occurs when there is no soot in the engine oil, only the low-hardness plates become worn when soot is present in the engine oil, and only the plate wear amount increases together with the soot concentration. In consideration of these results, it is thought that chain elongation occurs due to the presence of soot between the pins and plates, and that the main factor of this plate wear is three-body abrasive wear.

2.2. Influence of Different Oil Supply States on Chain Elongation

As described in Section 2.1, plate wear due to three-body abrasive wear is thought to be the main factor increasing chain elongation. However, when soot is present in the engine oil, increasing the oil supply rate increases the supply of soot that is a potential cause of three-body abrasive wear, so supplying oil is thought to increase the wear amount. Therefore, wear tests were performed with different oil supply rates and carbon black concentrations in the engine oil to confirm the influence of the oil supply status to the chain pin and plate sliding surfaces on chain elongation. The tests used a discrete wear tester in order to stabilize the oil supply conditions. Table 2 shows the specifications of the chain used in the tests and the test conditions. In addition, Fig. 4 and Fig. 5 show the pin and plate wear amounts. Figure 4 shows that increasing the oil supply rate reduced the pin wear amount for both carbon black concentration conditions of 0 wt% and 1.0 wt%. This

is thought to be because adhesive wear between the pins and plates is the dominant mode for pin wear, so increasing the oil supply rate helped prevent the oil film between the pins and plates from breaking, which reduced wear. In addition, under conditions of a carbon black concentration of 1.0 wt%, increasing the oil supply rate reduced the pin wear but increased the plate wear. This is thought to be because increasing the oil supply rate increased the amount of carbon black present between the pins and plates, so plate wear was accelerated by three-body abrasive wear.

Next, Fig. 5 shows that increasing the carbon black concentration increased the pin and plate wear under both oil supply rate conditions of 0.1 l/min and 1.0 l/min. The increase in plate wear is as described previously, but the pin wear also increased together with the increase in the carbon black concentration. This is thought to be because carbon black accumulated near the pin and plate sliding surfaces, which obstructed oil supply to the sliding surfaces and accelerated abrasive wear.

These results confirmed that oil supply is necessary to suppress pin surface wear in order to reduce chain elongation, but oil supply may also increase plate wear under conditions where soot is present in the engine oil. Therefore, excessive oil supply may accelerate chain elongation.

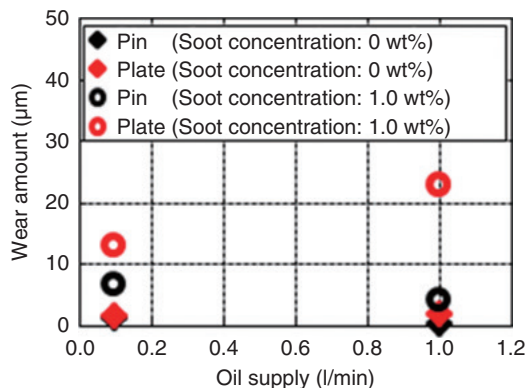


Fig. 4 Relation between wear amount and oil supply

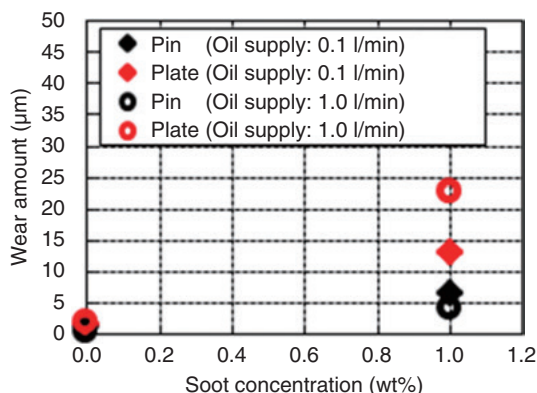


Fig. 5 Relation between wear amount and soot concentration

3. Chain Elongation Prediction Technology

3.1. Chain Elongation Predictive Formula

It was confirmed that the soot concentration in the engine oil is a factor increasing chain elongation. However, to predict the chain elongation rate, it is necessary to understand the influence of factors such as the contact surface pressure and velocity of the pin and plate sliding surfaces. Therefore, the chain elongation under different engine operating conditions was confirmed in engine bench tests to perform factor analysis. Figure 6 shows the test results arranged according to the condition of equal chain bending times. The bending and sliding distance results in Fig. 6 were obtained through tests with other factors held constant, so the trend can be easily understood. However, other factors mutually influence each other even when arranged according to the relationship between the respective chain elongation factor and the chain elongation rate. This makes it a challenge to understand the trends in the relationships between the chain elongation rate and factors such as contact surface pressure and velocity, and the influence of separate factors cannot be derived.

Therefore, correction was performed using the regression curves of other graphs in Fig. 6 so that factors other than the factor shown on the horizontal axis of each graph were constant conditions, and iterative calculations were performed until the slopes of all chain elongation factors converged. This enabled separate derivation of the influence of each factor on chain elongation. Figure 7 shows these calculation results. Whereas the results in Fig. 6 before the iterative calculations do not show a clear correlation between chain elongation factors and the chain elongation rate, the results in Fig. 7 after the iterative calculations show a sufficient correlation. Figure 7 also shows that chain elongation increases together with the pin and plate contact surface pressure and the sliding distance. In addition, chain elongation tends to increase as the sliding velocity decreases. Next, regarding the plate material characteristics, chain elongation decreases as the ratio of shear surface at the plate hole (the percentage of the plate hole machined surface accounted for by the shear surface) increases. In addition, chain elongation tends to decrease as the plate hole hardness increases, up to a certain hardness. This is thought to be because three-body abrasive wear due to soot is the dominant mode of plate wear, so the plates become resistant to wear as the hardness increases. However, these test results showed that chain elongation increases together with the hardness above a certain hardness. This is presumed to be due to the following reasons. A preload is applied to the chain to adjust the length and increase the fatigue strength. The chain plate holes deform when this preload is applied, and as the plate hardness decreases, the deformation amount increases, reducing the contact surface pressure between the pins and plates. The results in Fig. 7 also show that chain elongation tends to increase together with the contact surface pressure, and the phenomenon where chain

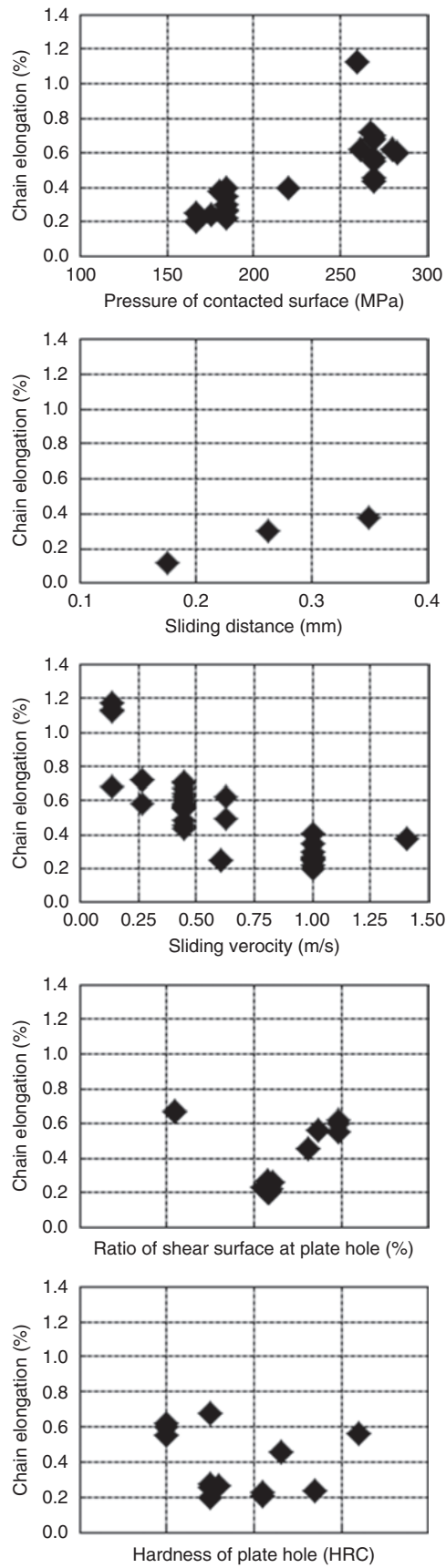


Fig. 6 Test results of relation between chain elongation and chain elongation factor

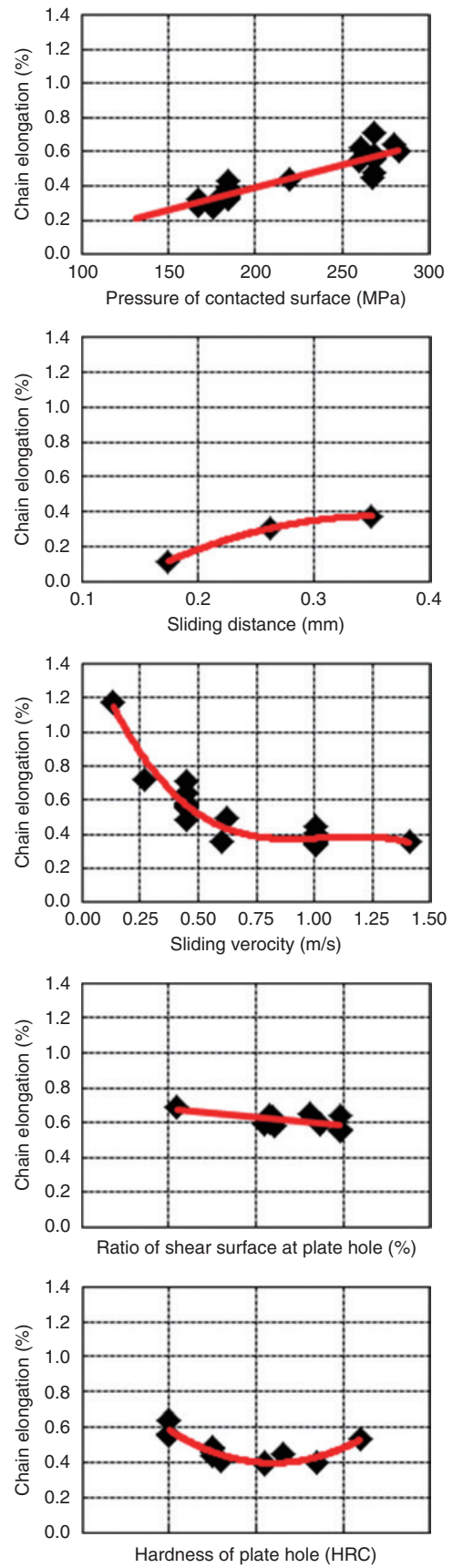


Fig. 7 Relation between chain elongation and chain elongation factor

elongation increases together with the hardness is thought to result from increased contact surface pressure due to a smaller deformation amount when the preload is applied. These results show that increasing the chain plate hardness effectively suppresses chain elongation, and reducing the hardness effectively lowers the contact surface pressure. Therefore, there is thought to be an optimum hardness for suppressing chain elongation.

Based on the results in Fig. 2 and Fig. 7, a formula was constructed that can predict the chain elongation rate from the specifications of the chain-driven system, the chain tension, engine speed $\times$ frequency (total revolutions), engine operating time, and the soot concentration in the engine oil. An outline of this predictive formula is shown below.

$$L = \{f(p) + g(v) + h(\alpha) + i(\beta)\} \times j(l) \times k(\rho) \times N$$

Here,

L : Chain elongation rate (%)

$f(p)$: First-order function of the contact surface pressure p

$g(v)$: Third-order function of the sliding velocity v

$h(\alpha)$: First-order function of the ratio of shear surface at the plate hole α

$i(\beta)$: Second-order function of the plate hole hardness β

$j(l)$: Second-order function of the sliding distance l

$k(\rho)$: Second-order function of the soot concentration in the engine oil ρ

N : Chain bending times

3.2. Verification of Chain Elongation Predictive formula

The chain elongation occurring in engine bench tests was compared with the calculation results to verify the chain elongation predictive formula. To perform verification under various operating conditions, tests were performed under various conditions other than the test conditions used to derive the predictive formula. These included constant speed tests at different engine speeds from low speed to high speed, variable speed tests in which the

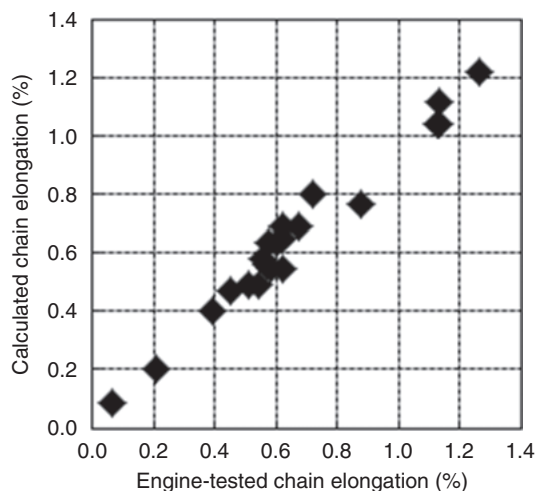


Fig. 8 Comparison of engine-tested values and calculated values

engine speed was varied during the test, and constant speed and variable speed tests using different load conditions. Figure 8 shows the verification results, and shows a high correlation between the test results and calculation result. This confirmed that the constructed predictive formula can be used to estimate chain elongation in an actual engine.

4. Conclusion

The chain elongation mechanism due to soot in the engine oil was analyzed and experiments were performed to obtain the relationship between chain elongation factors and the chain elongation rate with the aim of constructing chain elongation prediction technology. The following knowledge was gained as a result.

- (1) Chain elongation due to soot in the engine oil occurs as a result of soot present on the pin and plate sliding surfaces, and three-body abrasive wear is the dominant mode of plate wear.
- (2) Adhesive wear is the dominant mode of pin surface wear, so oil should be supplied to the pin and plate sliding surfaces. However, under conditions where soot is present in the engine oil, increasing the oil supply amount increases the plate wear, so excessive oil supply may accelerate chain elongation.
- (3) Use of an experimentally derived chain elongation predictive formula enabled estimation of chain elongation in the initial design stages.

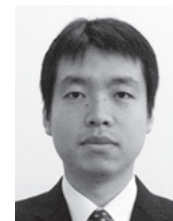
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