APPLICATION OF SUBLOADING-OVERSTRESS FRICTION MODEL TO FINITE ELEMENT ANALYSIS

T. Kuwayama[1], K. Hashiguchi[2], N. Suzuki[1], N. Yoshinaga[1] and S. Ogawa[1]

[1] Nippon Steel & Sumitomo Metal Corporation, Japan
[2] Kyushu University, Japan

Abstract:

Accurate prediction of contact behaviour between machine tools and metals is required for the mechanical design of machinery. In this article, the numerical analysis of the contact behaviour is described by incorporating the subloading-overstress model [6] which is capable of describing the contact behaviour for a wide range of sliding velocity including the increase of coefficient of friction with the increase of sliding velocity. And its validity is verified by the comparison with some test results. First, in order to examine the influence of sliding velocities on the friction properties, the flat-surface friction tests for lubricated interfaces between galvannealed steel sheet and SKD-11 tool steel were performed. As a result, It is observed that the friction smoothly translate to kinetic friction, after exhibiting the peak at the static friction. In addition, it is observed that the higher the sliding velocity, the larger the friction resistance, meaning the positive rate sensitivity. Then the subloading-overstress model is implemented in the finite element analysis program ABAQUS/Standard, and it is used to simulate the flat-surface friction tests. The predictions from the finite element analysis are shown to be in very good agreement with experimental results.

Keywords: friction; sliding; subloading-overstress friction model; numerical analysis; FEA

1 INTRODUCTION

To counter global warming, policies to subdue CO2 emissions have been taken by every country in the world. Concerning automobiles, current fuel economy regulations are under review in order to be further enhanced. Automobiles will be required to provide still stricter and improved fuel economy than current requirements.

A lighter vehicle may be an effective means for better fuel economy; however, no lighter vehicle can be permitted unless collision safety performance is secured. Compatible means between lighter vehicles and collision safety are requested.

As a feasible means for vehicles permitting compatibility between lighter weight and collision safety, it has been first considered that high-strength steel sheets are used for car bodies. As for the method for forming the shape of high-strength steel sheets in order to apply such to car body components, there are two types: cold forming and hot forming. Various steel types and methods appropriate for the respective forming methods are suggested. Second, it is conceivable to employ materials of low density such as aluminum, magnesium, and CFRP (carbon fiber-reinforced plastic).

In any of the above-stated methods, the mass production of auto body components is performed through a forming process using die-set represented by press forming. In order to avoid forming defects such as cracks through the suitable control of the material’s influx into the inside of a die-set, it is of great importance to know the exact friction properties of the die-set and materials. In particular, when a cold-press forming process of steel is assumed, the sliding velocities between the die-set and steel during forming vary over a wide range. Therefore, it is essential to assess the broadly-ranging friction properties of the sliding velocities in a high accuracy. In addition, forming processes are mostly simulated beforehand by the numerical analysis method to verify the validity of the process concerned. The above-mentioned friction properties in the sliding velocity over a wide range must be exploited by the implementation to numerical analysis methods in order to predict a forming process accurately.

The friction phenomenon can be formulated as a constitutive relation in a similar form to that of the elastoplastic constitutive equation of materials. A constitutive equation for friction with the transition from the static to the kinetic friction and vice versa has been formulated as the subloading-friction model by Hashiguchi et al. [1] and Hashiguchi and Ozaki [2]. It can also describe the accumulation of sliding displacement during a cyclic loading of tangential contact traction. However, it is capable of describing only the decrease of friction with the increase of sliding velocity, while the increase of friction with the increase of sliding velocity is observed in the friction behavior between lubricated solids [3][4][5]. Then, subloading-friction model was extended to describe the increase of the friction with the increase of sliding velocity by Hashiguchi et al. [6] by incorporating the overstress model for the viscoplastic constitutive equation. It is called the subloading-overstress friction model.

In this article, the subloading-overstress friction model is introduced into the finite element analysis. To begin with, the material parameters used for the present friction model were determined for the friction between the SKD-11 tool steel and a galvannealed (an alloyed hot-dipped galvanized) steel sheet. In addition, the present model was implemented in the ABAQUS/Standard for the numerical analyses. The validities of the subloading-overstress friction model and the FE analyses are verified by the comparisons with test results.

2 FRICTION EXPERIMENT

In order to examine the influence of sliding velocities on the friction properties, the flat-surface friction tests were performed as will be explained below.

The overview of the friction test apparatus is schematically depicted in Fig. 1. A flat steel sheet is sandwiched with a tool having flat contact planes by which various normal contact loads can be applied to the steel sheet through the hydraulic actuator. The flat steel sheet is pulled out from the tools at constant speed under constant normal contact load in each test. The pulling-out force of the steel sheet is measured by the load cell installed on the top of the steel sheet.

Coefficient of friction :

$\mu = f_t/f_n = T/2W$

where,

T : Pulling-out load

W : Normal contact load

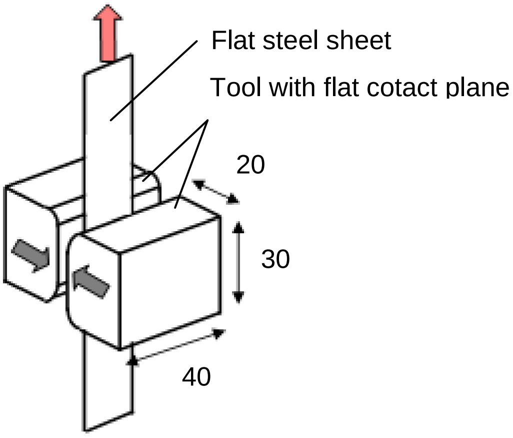

Fig.1 Schematic of flat-surface friction test

The test conditions of the friction tests conducted in this paper are shown in Table 1. Galvannealed steel sheets having a size of 300 mm in length, 30 mm in width, and 0.7 mm in thickness, with a tensile strength of 270 MPa, were used as flat steel sheets. Prior to the test, antirust oil was coated with a sponge on the surface of the flat steel sheets. The material quality of the tool used is the SKD-11 tool steel. The contact face of the tool was ground with abrasives for each test. The normal contact load was fixed at 5 kN when a flat steel sheet was sandwiched with the tool. Then, the average pressure of the contact surface was 5.8 MPa. The test was conducted at four levels of sliding-speed: 1 mm/min, 10 mm/min, 50 mm/min, and 200 mm/min, at which the flat steel sheets were pulled out.

Table.1 The test condition of the flat-surface friction test

No.	Test sheet	Tool	Normal contact load [kN]	Sliding speed (Pulled out speed) [mm/min.]
1	Galvannealed steel sheet	SKD-11 Tool steel	5	1
2				10
3				50
4				200

Pulling out was started 10 seconds after the normal contact load was applied. In order to clearly measure the transitional behaviour from the static friction to the kinetic friction, the load data was recorded under a fixed sampling rate of 0.8 kHz. The coefficient of friction was calculated by dividing the measured pulled-out load by twice the normal contact load, since the tools were in contact with the both sides of the flat steel sheet.

The variation in the friction resistance according to the sliding displacement is shown in Fig. 2, when the sliding velocity was varied according to four levels: 1 mm/min, 10 mm/min, 50 mm/min, and 200 mm/min.

In every sliding velocity, it is observed that the friction smoothly translate to kinetic friction, after exhibiting the peak at the static friction. In addition, it is observed that the higher the sliding velocity, the larger the friction resistance, meaning the positive rate sensitivity.

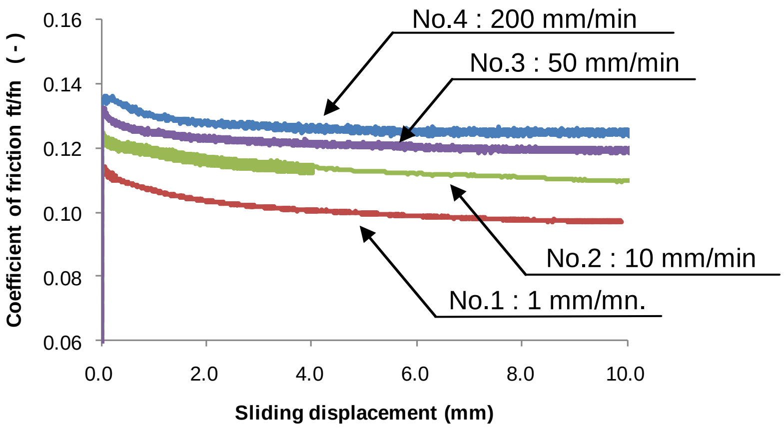

Fig.2 Variation of fricton coefficient with the sliding displacement

3 SUBLOADING-OVERSTRESS MODEL FOR FRICTION

The subloading-overstress friction model [6] is reviewed briefly in this section. It will be applied to the prediction of the test results described in the last section: 1) the smooth transition from the static friction to the kinetic friction, and 2) the positive rate sensitivity, i.e. the increase of friction force with the increase of sliding velocity. The method for determining the material parameters used in the present model is also described in this section.

3.1 Subloading-overstress friction model

In the present model, *Sliding-dynamic loading surface* that the current stress passes through always and has a circular cone shape similarly to the sliding-yield surface is given in the following equation, where, $\mathbf{f}_t$ is the tangential load (friction) and f_n is the normal contact loads, r $(0 \le r \le r_m)$ is called the *dynamic loading ratio that* is the ratio of the size between *Sliding-dynamic loading surface* and sliding-yield surface, and μ is the coefficient of friction defining the size of sliding-yield surface. r_m is the maximum value of r as will be described later.

$$\|\mathbf{f}_t / f_n\| = r\mu \tag{1}$$

First, the evolution rule of a coefficient of friction μ is formulated to predict the test result: 1) the smooth transition from the static friction to the kinetic friction. Second, the relationship between viscoplastic sliding velocity $\bar{V}^{vp}$ and *dynamic loading ratio* r is also formulated to predict the test result: 2) the positive rate sensitivity.

3.2 Characterization of the evolution rule of a coefficient of friction

To predict the test result: 1) the smooth transition from the static friction to the kinetic friction, the evolution rule of a coefficient of friction μ is given in the following equation, where, μ_s and μ_k are the maximum and the minimum of μ, respectively, κ and a are the material constants defining a decreasing rate of μ due to plastic sliding, and ξ and b are material constants defining a recovering rate of μ according to the elapsed time.

$$\dot{\mu} = -\kappa\left\{\mathrm{e}^{a(\mu-\mu_k)} - 1\right\}\|\bar{V}^{vp}\| + \xi\left\{\mathrm{e}^{b(\mu_s-\mu)} - 1\right\} \tag{2}$$

Deterioration and reformation are described by the first term and the second term in Equation (2), respectively. In the present case, ξ was considered to be zero because the effect of the second term is negligible since the present case is focused on the state at a high sliding velocity. Therefore, no identification of the material constants of b is conducted.

The results of the friction resistance obtained from the tests at a sliding velocity of 1 mm/min are rearranged and presented in Fig. 3 as the relationship between the time-derivative of the friction resistance in the vertical axis and that in the horizontal axis.

The two material constants κ and a were identified by approximating in accordance with the least square method in order to be consistent with the test results shown in Fig. 3. Then, μ_k=0.098 was given as the material coefficient of μ_k, based on the test results shown in Fig. 2. The parameters used in the Equation (2) are shown in Table 2.

In comparison of the friction test results in the four level of sliding velocities shown in Fig. 2, it emerges that the decrease rate of the coefficient of friction in the transition from the static friction to the kinetic friction is approximately 10 percent, irrespective of the sliding speed, etc.; thus, the damping behaviours of the coefficients of friction are identical. This fact allows us to assume that the value of the material constants κ and a, identified by the test result at the sliding velocity of 1 mm/min in the present study, is applicable with respect to other sliding velocities.

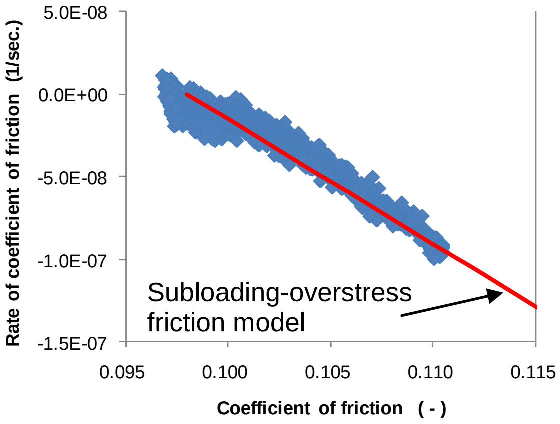

Fig.3 Measured coefficient of friction

Table.2 The parameters used in the Equation (2)

μ_s [-]	μ_k [-]	κ [1/mm]	a [-]	ξ [1/msec.]	b [-]
0.115	0.098	0.045	1	0	N/A

3.3 Characterization of the relationship between sliding velocity and dynamic loading ratio

To predict the test result: 2) the positive rate sensitivity, i.e. the increase of friction force with the increase of sliding velocity, the relationship between viscoplastic sliding velocity $\bar{V}^{vp}$ and *dynamic loading ratio* r can be given by the following Equation (3) in the present model. Where, r_s is a *sliding-normal-yield ratio* varies between 0 and 1 in accordance with the development law separately defined. [6] In addition, r_m is a *dynamic loading limit ratio* and provides the maximum of *dynamic loading ratio* r, and was fixed at 1.8 in the present study. η_v and n are the material constants.

$$||\bar{V}^{vp}|| = \frac{1}{\eta_v}\frac{\langle e^{n(r-r_s)}-1\rangle}{r_m-r} \tag{3}$$

In the present model, the *dynamic loading ratio* r is a parameter to describe an overstressed state and has a value not less than the *sliding-normal-yield ratio* r_s and, in addition, not more than the *dynamic loading limit ratio* r_m. Equation (3), defining the corresponding relation of the *dynamic loading ratio* r with the viscoplastic sliding velocity $\bar{V}^{vp}$, enables us to describe the property such that the higher the sliding velocity, the larger the friction resistance (positive rate sensitivity).

Only in order to identify the material constants in Equation (3), the following Equation (4) was obtained through linearly approximating the relationship between sliding velocity $\|V\|$ (mm/min) and the coefficient of kinetic friction μ_k obtained from the above-mentioned experiments, as well as through assuming that $\|V\|$ is equal to $\|\bar{V}^{vp}\|$.

$$\mu_k = \alpha \ln(\|\bar{V}^{vp}\|) + \beta = 4.20 \times 10^{-3} \ln(\|\bar{V}^{vp}\|) + 0.100 \tag{4}$$

The coefficient of friction when the sliding displacement is quasi-statically generated (the coefficient of quasi-static friction) was considered to be μ_{k0}=0.078, which was a coefficient of kinetic friction at a sufficiently low sliding velocity of $\|\bar{V}^{vp}\|$=0.006 mm/min — calculated based on Equation (4). The experimental values of the *dynamic loading ratio* r were obtained through dividing the coefficient of friction at each sliding velocity by the above coefficient of quasi-static friction. The above relationship of the experimental values of the *dynamic loading ratio* r with the viscoplastic sliding velocity $\|\bar{V}^{vp}\|$ is marked with the small blue solid circles in Fig. 4.

The identification of the material constants η_v and n was conducted so that the experimental values of such could be consistent with Equation (3), in accordance with the least square method. The parameters used in the Equation (3) are shown in Table 3.

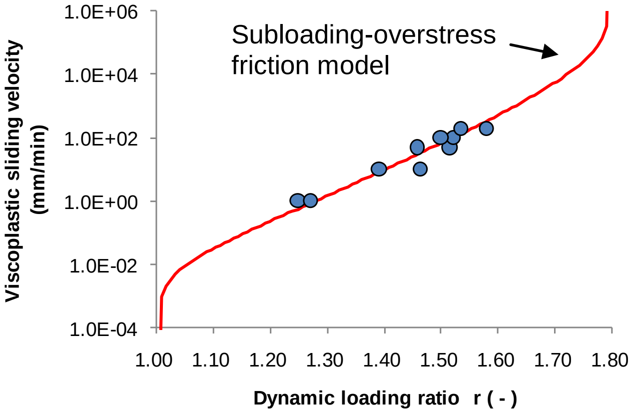

Fig.4 Relation of viscoplastic sliding velocity vs. *dynamic loading ratio* r

Table.3 The parameters used in the Equation (2)

η_v [msec./mm]	n [-]	r_m [-]
1.15×10^7	16.52	1.8

4 APPLICATION TO FINITE ELEMENT ANALYSIS

It should be verified whether the present model consistently-predict the two experimental results: 1) the smooth transition from the static friction to the kinetic friction, and 2) the positive rate sensitivity, i.e. the increase of friction force with the increase of sliding velocity.

For verifying the validity of the present model, the friction behavior was analyzed through numerical modeling of a flat-surface friction test as shown in Fig. 5, and it was followed by using the material parameters identified by the above-mentioned method.

A finite element analysis program, ABAQUS/STANDARD, was used for the analyses. ABAQUS is capable of implementing an arbitrary friction constitutive equation that includes state parameters such as contact pressure and sliding velocities via user-subroutines, and the present model was also implemented in ABAQUS/STANDARD with the user-subroutines. Analysis was performed by using eight-node hexahedron element with each side length 10 mm and the elastic moduli of E =206 GPa, ν =0.3, in the following two processes as shown below. Time step used for the analysis was decided by ABAQUS, which will choose the largest time increment on efficiency.

STEP 1: Hexahedron element(C3D8) was arranged in a rigid surface and subsequently pressed against the rigid surface with a contact pressure of 5.8 MPa (the same value as in the experiment).

STEP 2: Forced displacement rates are given in the tangential direction with respect to the element.

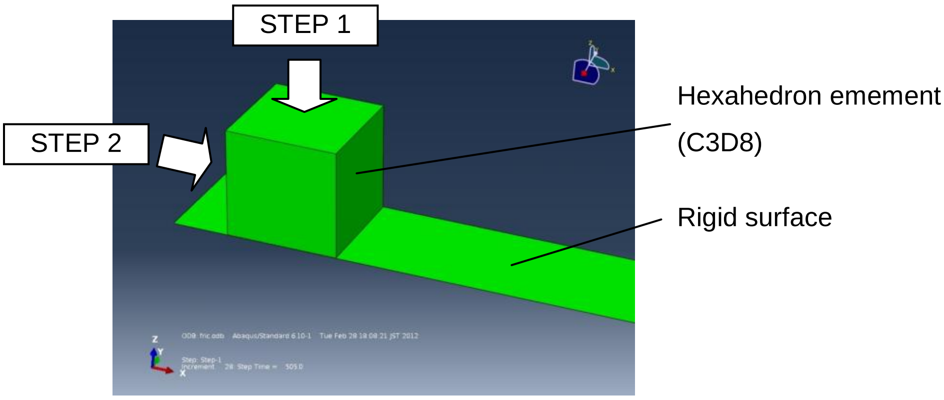

Fig.5 FE model of flat-surface friction test

The results of the analyses together with those in the experiments are shown in Fig. 6. The open-marks plotted in Fig. 6 show the experimental results, which were obtained through partially omitting those in Fig 2. In addition, the results of the analyses shown by the solid lines indicated in the figure are the coefficients of friction.

It is conceivable from the present result that the analysis by the present friction model allows us to reflect the smooth transition from the static friction to the kinetic friction observed in the experiments accurately. In addition, it enables us to reflect the properties in high accuracy, such that the higher the sliding velocity, the larger the friction resistance (positive rate sensitivity).

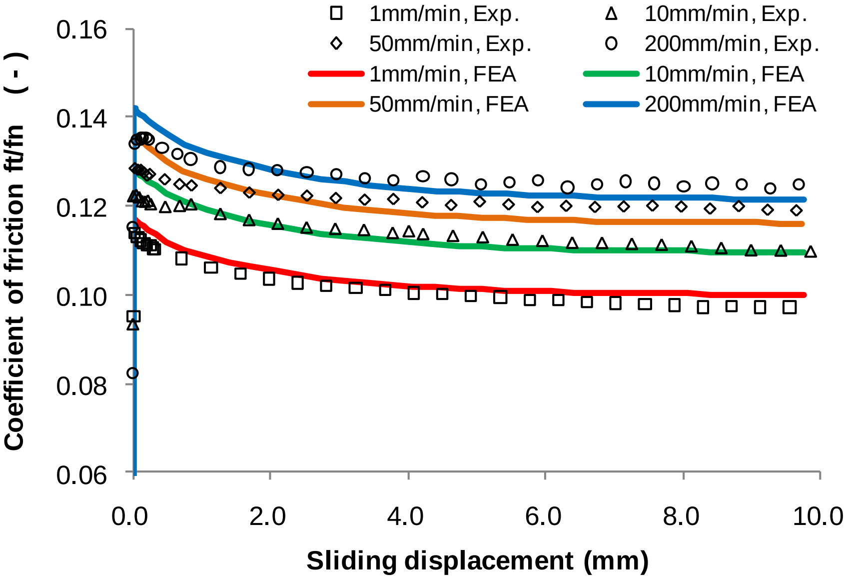

Fig.6 A comparison between predected and observed coefficient of friction f_t/f_n

5 CONCLUSIONS

The subloading-overstress friction model proposed by the authors [6] was implemented to the finite element analysis program ABAQUS/Standard and applied to the prediction of sliding behavior of metals in this paper. In addition, the friction tests for lubricated interfaces between galvannealed steel sheet and SKD-11 tool steel have been performed in order to evaluate the applicability of the finite element analysis program to real friction behavior of metals. Then, the following results are obtained in the present study.

1. The smooth transition from the static to the kinetic frictions is predicted in high accuracy.
2. The positive-rate sensitivity, i.e. the increase of friction force with the increase of sliding velocity is predicted qualitatively well.

In order to further improve the accuracy of prediction, return-mapping algorithm should be incorporated into the present friction model. Further study will be executed in order to predict the actual sliding behavior in the metal forming processes as the engineering practice.

6 REFERENCES

[1] Hashiguchi, K., Ozaki, S., and Okayasu, T. : Unconventional friction theory based on the subloading surface concept, Int. J. Solids Structure, Vol.42, pp.1705-1727, 2005.

[2] Hashiguchi, K., and Ozaki, K. : Constitutive qauation for friction with transition from static to kinetic friction and recovery of static friction, Int. J. Plasticity, Vol.24, pp2102-2124, 2008

[3] Gearing, B.P., Moon, H.S., Anand, L. : A plasticity model for interface friction : application to sheet metal forming, Int. J. Plasticity, Vol.17, pp237-271, 2001

[4] Norihisa, T., Itoigawa, F., Nakamura, T. : Study on Velocity-Dependent Property of Friction in Boundary Lubrication under Low Contacting Pressure Condition, J. Japanese Society of Tribologists, Vol.53, pp682-688. 2008

[5] Muraki, M.,Oshima, A.: Friction-Velocity Characteristics of Oils Containing Zinc Dialkyldithiophosphates and Analysis of Their Tribofilms, J. Japanese Society of Tribologists, Vol.56, pp523-529. 2011

[6] Hashiguchi, K., Kuwayama, T., Suzuki, N., and Ogawa, S. : Time-dependent friction model : Subloading-overstress friction model, Proc. 17th Japan Computational Engineering Conference, Vol.17, NO.C-9-1. 2012