Research Report

Estimation of Spray Lubrication and Die Temperature for Die Wear Life Prediction in Hot Forging

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熱間鍛造型寿命予測のためのスプレー潤滑特性と型温評価

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Abstract

We have been developing a process design CAE system to predict die wear life in the process design stage for the hot forging of steel. Our goal is to reduce production costs by shortening the development period, while maximizing the life of the die. In our system, we use an expression that defines the relationship between die wear, die strength, and friction factors, such as die pressure, sliding speed, and the coefficient of friction. To predict the die wear life with high precision, it is important to obtain the actual coefficient of friction and the heat transfer coefficient for use in a die temperature analysis that considers both heat and deformation. It is also important to clarify the effect of these friction factors on the die softening and wear. For this study, we considered the use of a hot forging die with a forging machine that is typically used for the production of connecting rods and so on. We determined the lubricant adhesion and the heat transfer coefficient variation that results from spraying lubricant, by performing a lubricant spray model test. Moreover, we devised a new hot ironing test to obtain the relationship between the coefficient of friction and the lubricant conditions, as well as the relationship between the friction factors and die temperature.

Keywords: Forging, Hot ironing, Lubricant spray, Lubricant adhesion, Heat transfer coefficient, Die temperature, Spray mist density, Spray pressure on die, Coefficient of friction, Dilution of lubricant in water, Die wear life prediction

要　旨

鋼の熱間鍛造において，工程設計段階で型摩耗寿命を予測し得る工程設計支援システムの開発を行っている。その目的は，生産準備期間の短縮や長寿命な型設計による生産コストの低減である。このシステムでは，型摩耗量と面圧，すべり速度，摩擦係数等の摩擦因子や型強度との関係を式で表している。型摩耗寿命を高精度で予測するためには，熱-変形連成温度解析に必要な実際の摩擦係数や熱伝達係数を得ることが重要である。また，型軟化や摩耗に対するそれらの摩擦因子の影響割合を明らかにすることも重要である。我々が現在開発しているシステムでの対象型は，コンロッドなどの生産に使用している鍛造機用の熱間鍛造型である。我々は，潤滑剤スプレーモデル試験を用いて，潤滑剤スプレーによる潤滑剤付着性および冷却における熱伝達係数の変化を得た。また，我々は新たに熱間しごき形試験法を提案し，潤滑条件と摩擦係数の関係や摩擦因子と型温度の関係を得た。

キーワード　鍛造，熱間しごき加工，潤滑剤スプレー，潤滑剤付着量，熱伝達係数，型温度，スプレー噴霧密度，スプレー受圧力，摩擦係数，潤滑剤水希釈倍率, 型寿命予測

1. Introduction

To improve our competitiveness in the hot forging of steel parts, it is vital for us to reduce our production costs. If we can predict the die wear life, which constitutes about 70 % of the total hot forging die life, we will be able to reduce our production costs by shortening the development period and by being able to design long-life dies. Therefore, we are developing a process design CAE system[1] to predict the die wear life in the process design stage of hot forging. In this system, we use an expression that links die wear, die strength, and friction factors such as die pressure, sliding speed, and the coefficient of friction. To predict the die wear life with high precision, it is important for us to obtain the actual coefficient of friction and the heat transfer coefficient so that we can perform a die temperature analysis that considers both heat and deformation. It is also important for us to clarify the effects of the friction factors on the die softening and wear.

This paper considers a hot forging die that is used with a forging machine, which is typically used for producing connecting rods and so on. We used a lubricant spray model test to analyze the lubricant adhesion and the heat transfer coefficient. Moreover, we present a newly devised hot ironing type test and investigate the influence of the coefficient of friction on the lubricant conditions, as well as the relationship between the friction factors and the die temperature.

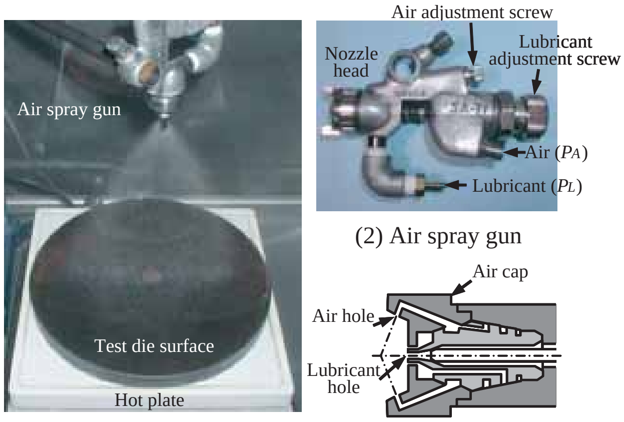
2. Estimation methods

2. 1 Lubricant spray model test

The lubricant spray model test method is illustrated in **Fig. 1**. We used an air-powered spray gun to reproduce the spray conditions applied in actual production. We sprayed lubricant for 0.5 seconds onto the test die surface (diameter 240 mm ×thickness 20 mm, hot die steel), that was being heated on a hot plate. At the center of the test die surface, we embedded a lubricant adhesion measurement die or a cooling thermometry die (diameter 20 mm×thickness 20 mm). We used a white-type lubricant that we diluted with water.

The conditions of the lubricant spray model test are listed in **Table 1**. The spray mist density was defined as the amount of lubricant that reaches the die per unit time and per unit area. We installed a water-absorbing seal in the plastic case (inner measurements 32 mm×32 mm×9 mm), and estimated the spray mist density from the change in the weight of the sprayed area. We measured the spray pressure on the die by using a small pressure sensor (rated capacity 0.2 MPa) with an outer diameter of 6 mm. The 0.4-mm diameter holes in the cooling thermometry die were drilled from the opposite side of the test die surface to a depth of 0.5 mm, 1 mm, and 2 mm. A Chromel-Alumel sheathed thermocouple with a diameter of 0.25 mm was inserted into the hole, and then capped with a conductive resin material.

We determined the amount of lubricant that had adhered from the change in the weight of the lubricant adhesion measurement die and by visual observation of the center of the test die surface. The heat transfer coefficient was determined from the



(1) Testing device (2) Air spray gun (3) Nozzle head

Fig. 1 Lubricant spray model test.

Table 1 Lubricant spray model test conditions.

Parameter	Test conditions
Lubricant	White-type lubricant B
Dilution of lubricant in water (vol.)	5, 10, 15 times
Spray time (s)	0.5
Spray nozzle internal diameter (mm)	1
Distance to test die surface (mm)	200
Spray mist density ρ_S (cc・s^{-1}・cm^{-2})	0.03, 0.1, 0.3, 0.5
Lubricant pressure P_L (MPa)	0.1, 0.2, 0.3
Air pressure P_A (MPa)	0.1, 0.2, 0.3
Die temperature T (℃)	150 to 400

relationship between the temperature measured at a depth of 0.5 mm from the test surface, the temperature 0.5 seconds after the start of the test, with the actual computation being done using 1-dimensional axial symmetry model heat-conduction analysis.

2. 2 Hot ironing test

We devised a new hot ironing test, which is illustrated in **Fig. 2**. In this ironing test, a constant sliding load is applied to the ironing die surface by using a billet with a square bar. Moreover, by changing the billet length, we can fix the contact time, sliding velocity, and the sliding length used for the ironing test. While many ironing-type friction evaluation tests[2, 3] have been proposed, our new test can measure both the coefficient of friction and the inner temperature of the ironing die.

The heated billet of square bar shape are placed on bending dies, and then immediately subjected to the impact of a punch, which deforms them into a U-shape. Then, the outside face of the billet are ironed with ironing dies with a gap, the width of which is narrower than the thickness of the billet. The billet is heated for about 60 s using high-frequency induction heaters until it reaches the test temperature. The configuration of the punch, bending die, and the ironing die used for the thermometry are shown in **Fig. 3**. The inner temperature of the ironing die is measured in the same way as in the lubricant spray model test. Under all the test conditions, after the billet has been heated to 150 °C, it is dipped into graphite lubricant to reduce the amount of oxidation. The ironing dies and the bending dies are heated using a rod heater embedded into the base of the die. The coefficient of friction is calculated using the formula shown in **Fig. 4**. The load components in the sliding direction and the vertical direction, produced on the sliding surface of the ironing die are calculated from the ironing load and the ironing lateral load. Using the actual measurements obtained at depths of 0.5 mm and 1 mm, the die surface temperature is calculated using a formula which was approximated from the difference for the unsteady state heat conduction equation for one dimension. The lubricant spray conditions used in the hot ironing test are listed in **Table 2**.

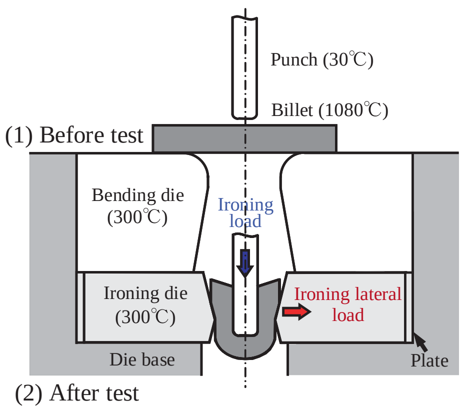


Fig. 2 Hot ironing test.

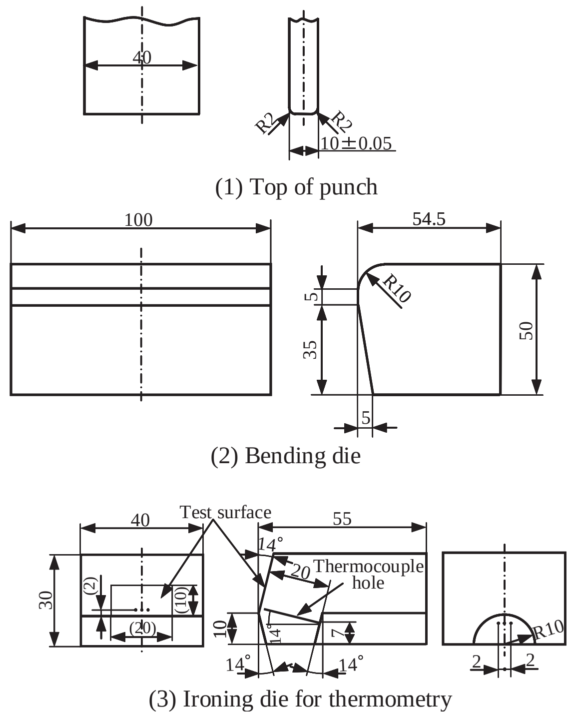


Fig. 3 Configuration of punch, bending die, and ironing die for thermometry in hot ironing test. Die material is hot die steel. Die surface roughness is 6.3 Rz.

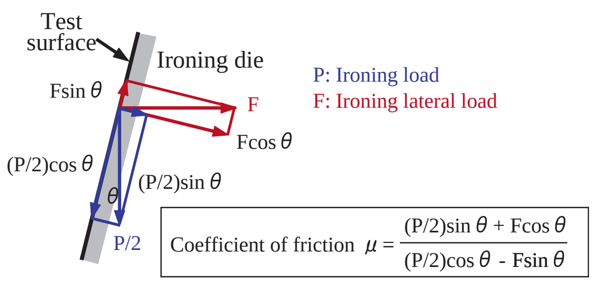


Fig. 4 Calculating coefficient of friction in hot ironing test.

3. Results

3. 1 Lubricant adhesion

The values obtained for the lubricant adhesion are given in **Table 3**. The best adherence was obtained with a lubricant that had been diluted five times in water, a spray mist density, ρ_s, of 0.1 cc・s^{-1}・cm^{-2}, and a die temperature, T, of 250 to 300 ^{o}C. For a given spray mist density, the die temperature range in which the amount of lubricant adhering increases, so that the spray pressure on the die becomes high, and the die temperature at which the greatest amount of lubricant adheres is also higher. When using lubricant that had been diluted 15 times in water, the lubricant failed to adhere under the majority of spray conditions. Therefore, we concluded that the dilution of lubricant in water, the spray mist density, die temperature, and spray pressure on the die all influence the lubricant adhesion greatly.

3. 2 Heat transfer coefficient

The effects of spray mist density and die temperature on the heat transfer coefficient in spray cooling are shown in **Fig. 5**. The heat transfer coefficient increases together with the spray mist density, and under all the spray mist density conditions, the maximum heat transfer coefficient was found to exist in the examined die temperature range. Moreover, for a spray mist density, ρ_s, less than or equal to 0.3 cc・s^{-1}・cm^{-2}, the heat transfer coefficient changed considerably with the die temperature. In the case of a spray mist density, ρ_s, of 0.1 cc・s^{-1}・cm^{-2}, no cooling is produced for die temperatures of 300 ^{o}C or more. The effect of the spray pressure on the die, and that of the die temperature on the heat transfer coefficient are shown in **Fig. 6**. For a given spray mist density, ρ_s, of 0.3 cc・s^{-1}・cm^{-2}, the heat transfer coefficient becomes large as the spray pressure on the die becomes high, at die temperatures of 300 ^{o}C or less. Therefore, we were able to conclude that the spray mist density, die temperature, and spray pressure on the die all greatly influence the heat transfer coefficient.

Table 2 Lubricant spray conditions in hot ironing test.

Lubricant condition	Lubricant	Dilution of lubricant in water (vol.)	Spray mist density ρ_S (cc・s^{-1}・cm^{-2})	Die temperature T (℃)
A	White-type lubricant B	15 times	0.3	300
B		5 times	0.1	
C	Graphite lubricant			

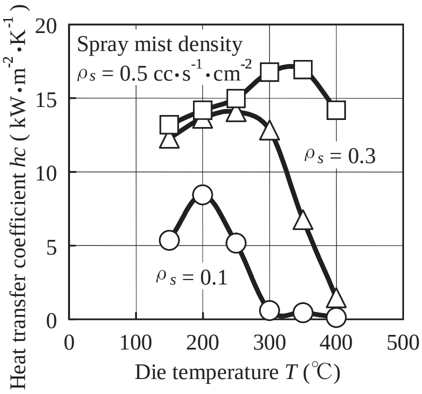


Fig. 5 Effects of spray mist density and die temperature on heat transfer coefficient in spray cooling.

Table 3 Lubricant adhesion results obtained from lubricant spray model test.

Dilution of lubricant in water (vol.)		5 times							10 times	15 times				
Spray mist density ρ_s (cc・s^{-1}・cm^{-2})		0.03	0.1			0.3		0.5	0.1			0.3		0.5
Lubricant pressure P_L (MPa)		0.1			0.3	0.1	0.2	0.3	0.1				0.2	0.3
Air pressure P_A (MPa)		0.1		0.3		0.1	0.3		0.1		0.3	0.1	0.3	
Spray pressure on die P_S (kPa)		1.4	0.7	0.9	1.3	0.5	1.0	1.1	0.7	0.7	0.9	0.5	1.0	1.1
Die temperature T (℃)	150	△	△	△	△	△	△	△	△	△	△	△	×	×
	200	○	△	△	△	△	△	△	△	△	△	△	×	×
	250	△	○	◎	△	△	△	△	○	×	×	×	×	×
	300	×	△	◎	◎	△	×	×	×	×	×	×	×	×
	350	×	×	×	○	△	△	×	×	×	×	×	×	×
	400	×	×	×	△	△	○	△	×	×	×	×	×	×

Relationship between lubricant adhesion and evaluation mark:
× ; 0 to 1 g・m^{-2}, △ ; 2 to 4 g・m^{-2}, ○ ; 5 to 7 g・m^{-2}, ◎ ; 8 to 10 g・m^{-2}

3. 3 Coefficient of friction

The effects of the lubricant on the coefficient of friction in the hot ironing test are shown in **Fig. 7**. For lubricant condition A (described in Table 2), the coefficient of friction is constant at about 0.2 throughout the ironing test. For lubricant condition B, the coefficient of friction increases from about 0.12 to about 0.2 as the ironing test distance increases. In the case of lubricant condition C, the coefficient of friction increases slightly from about 0.07 to about 0.1 as the ironing distance increases. From these three sets of results, we determined that the variation in the coefficients of friction was influenced by the adhesive strength of the lubricant. Therefore, we can say that the lubricant adhesion and the type of the lubricant greatly influence the coefficient of friction.

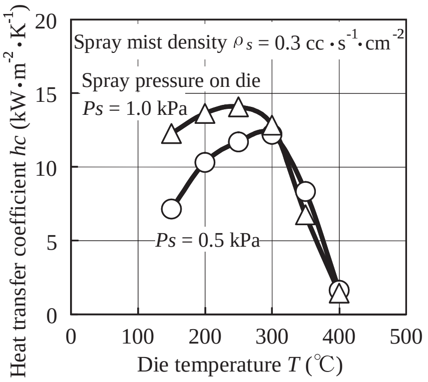


Fig. 6 Effects of spray pressure on die and die temperature on heat transfer coefficient in spray cooling.

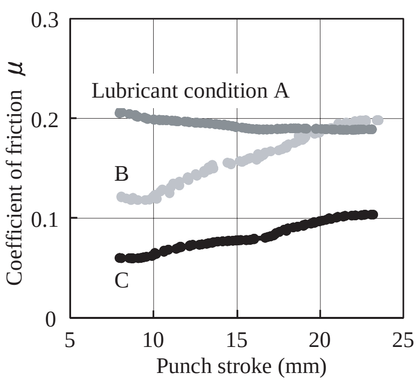


Fig. 7 Effects of lubricant condition on coefficient of friction in hot ironing test. (Billet temperature = 1080 °C; Sliding velocity = 190 mm・s^{-1}; Contact time = 0.18 s.)

3. 4 Ironing die surface temperature

An example of the die thermometry results obtained from the hot ironing test, as well as the estimated die surface temperature results, are shown in **Fig. 8**. The die surface temperature begins to rise about 0.05 s after the start of the ironing test. This time is equal to that needed for the billet to reach the temperature measurement part. In Fig. 8, ΔT is the increase in the die surface temperature. The effect of the coefficient of friction on the increase in the die surface temperature ΔT is shown in **Fig. 9**. If the coefficient of friction changes from 0.1 to 0.3, ΔT will be about 30 °C. The effect of the sliding

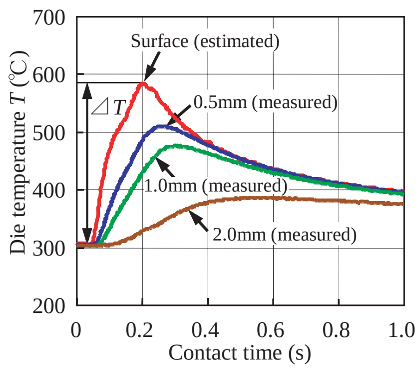


Fig. 8 Example of estimated die surface temperature and measured inner die temperature in hot ironing test. (Billet temperature = 1080 °C ; Sliding velocity = 190 mm・s^{-1} ; Contact time = 0.18 s; ΔT = increase in die surface temperature.)

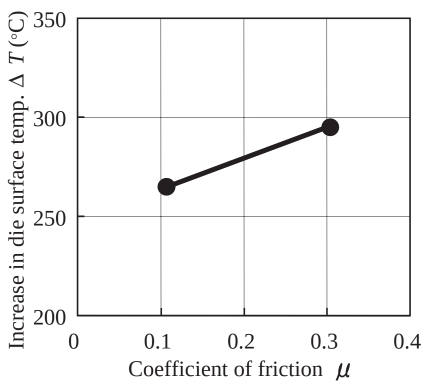


Fig. 9 Effect of coefficient of friction on increase in die surface temperature hot ironing test. (Billet temperature = 1080 °C ; Sliding velocity = 190 mm・s^{-1} ; Contact time = 0.18 s.)

velocity on ΔT under lubricant condition C is shown in **Fig. 10**. If the sliding velocity changes from 100 to 200 mm $\cdot$ s^{-1}, ΔT will be about 30 ^{o}C. The effects of contact time on ΔT under lubricant condition C are shown in **Fig. 11**. If the contact time changes from 0.15 to 0.3 s, ΔT is about 120 ^{o}C. Therefore, we determined that the contact time has the greatest influence on the increase in the die surface temperature.

4. Conclusions

We used a lubricant spray model test to analyze lubricant adhesion and the heat transfer coefficient. Moreover, we devised a new hot ironing test and we measured the ironing load, the ironing lateral load, and the inner temperature of the ironing die, in order to research the influence of the coefficient of friction on the lubricant conditions, as well as the relationship between the friction factors and the die temperature. As a result, we reached the following conclusions.

(1) The dilution of lubricant in water, the spray mist density, the die temperature, and the spray pressure on the die all have a great effect on the lubricant adhesion.

(2) The spray mist density, the die temperature, and the spray pressure on the die all greatly influence the heat transfer coefficient.

(3) The lubricant adhesion and the type of the lubricant both greatly influence the coefficient of friction.

(4) The contact time has the greatest influence on the increase in the die surface temperature.

In our subsequent studies, we will calculate the heat transfer analysis temperature of the die using the measured heat transfer coefficient. Moreover, we will investigate the effects of the friction factor on die softening and wear in a hot ironing test.

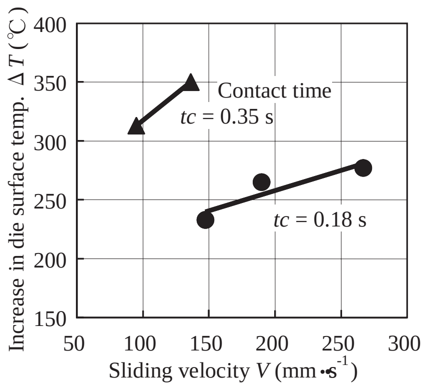


Fig. 10 Effect of sliding velocity on increase in die surface temperature under lubricant condition C in hot ironing test. (Billet temperature = 1080 ^{o}C.)

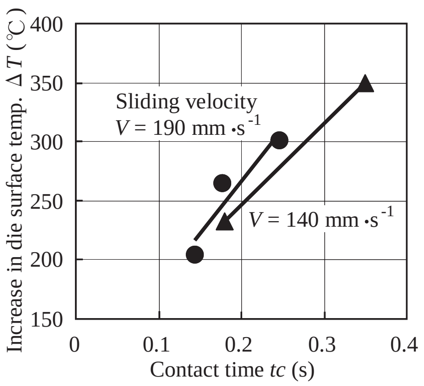


Fig. 11 Effect of contact time on increase in die surface temperature under lubricant condition C in hot ironing test. (Billet temperature = 1080 ^{o}C.)

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The publisher regrets that the following error had not been corrected. It is reproduced correctly as of April 25, 2005.
p.55 <left column, first line>
<left column, fourth line>
<the caption of Fig. 10 and Fig. 11>
<Error> condition A <Correction> condition C

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