

Prediction of Hot Forging Die Life Using Wear and Cooling Model

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熱間鍛造金型の摩耗予測式と吹付け冷却モデル

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Abstract

Hot forging is a manufacturing method that is applied to a wide variety of high-strength automotive components. To satisfy demands for lower costs and shorter production preparation times, it is vital that we be able to predict the die life. Around 70 % of the die failures that occur in hot forging processes result from the wear that occurs as the temperature of the die increases.

In this paper, we describe a newly developed technology that can be used to predict the temperature and wear of the dies used in hot forging. Through an examination of axisymmetric dies, we found that the amount of wear in the dies can be forecast using a model composed of the cumulative friction work of the

metal flow on the surfaces of the dies and the yield strengths of the die materials at elevated temperatures. We also found that the die temperature can be predicted by applying a cooling model that considers the relationship between the heat transfer coefficient and the Reynolds number of the lubricant jets that are generally used in hot forging. Using the cooling and die load models, we were able to determine the hot forging die life with sufficient accuracy at the process design stage. We have also developed a process design CAE system, based on our wear and cooling models, which is capable of predicting the die wear life and temperature.

Keywords

Hot forging, Die life, Wear, Prediction, Process design, CAE, Jet, Cooling, Heat transfer coefficient

要 旨

自動車用強度部品の素形材は熱間鍛造により大量に生産されており、一層のコスト低減や生産準備期間の短縮が求められている。この型寿命の70%は型温度上昇と関連した摩耗である。そこで、熱間鍛造金型の温度と摩耗量を設計段階で予測、寿命確保するための技術を開発した。第1ステップとして、軸対称金型を対象に検討し、金型の摩耗は、型表面を流動する材料により生ずる摩擦仕

事量と温度上昇によって軟化した型強度からなる予測式により求められることを明らかにした。次いで、熱間鍛造時に噴流方式で潤滑剤を吹付ける場合の状態量としてレイノルズ数を取り上げ、金型冷却能との関連を解明した。その結果、温度予測が可能な冷却モデルを提案した。これらの摩耗や冷却モデルを用いて、工程設計段階で金型温度と摩耗寿命を予測するシステムを構築した。

キーワード

熱間鍛造, 金型寿命, 摩耗, 予測, 工程設計, CAE, 水流吹付け, 冷却, 熱伝達係数

1. Introduction

Hot forging is a manufacturing method that is applied to a wide variety of high-strength automotive components such as crankshafts, connecting-rods, and transmission gears. There are two types of hot forging, namely, horizontal (hot former) and vertical. The horizontal type is applied to the high-speed forging of axisymmetric rounded parts such as gear blanks, while the vertical type is used for the manufacture of non-axisymmetric rounded parts such as connecting rods. In both cases, 70 % of die failures are a result of wear.¹⁾ Therefore, the prediction of die failure due to wear is vital to our being able to reduce manufacturing costs by shortening the production preparation time and realizing the design of dies with an extended life.

On the other hand, with the progress of numerical analysis technologies,²⁾ it has become possible to analyze not only the deformation of materials in hot forging processes, but also the mechanical and thermal loads imposed on the surfaces of the dies. In a previous paper, we described how the surface damage mode of dies at any given number of forging cycles can be predicted using CAE to analyze the loads on the dies in the process design stage.³⁾ That is to say, wear or other die damage modes can be forecast by using the method illustrated in **Fig. 1**, together with damage data and a database of actual

die material properties.

In this research, a die wear equation was constructed from the relationship between the calculated die loads and the degree of wear observed in actual dies to realize the prediction of the die life at any given number of forging cycles.

At the same time, through experimental analyses, the performance of different cooling conditions was quantified in terms of heat transfer coefficients, so that the temperature of the dies can be obtained at any given number of cycles without having to measure the decrease in the hardness of the die on the spot.

The results of evaluating the die cooling ability (heat transfer coefficient) through model-based experiments are also described, together with a die temperature prediction system that is related to the prediction of the amount of wear in the hot forging dies. Here, the evaluated jet cooling method is used for the horizontal high-speed hot forging machines which were examined in the derivation of the wear equation discussed above.

2. Prediction of die wear in hot forging

2.1 Wear model

In recent years, some wear equations for forging have been proposed,⁴⁾ but these failed to give the relationship between the amount of wear and the number of forging cycles. To solve this problem, we

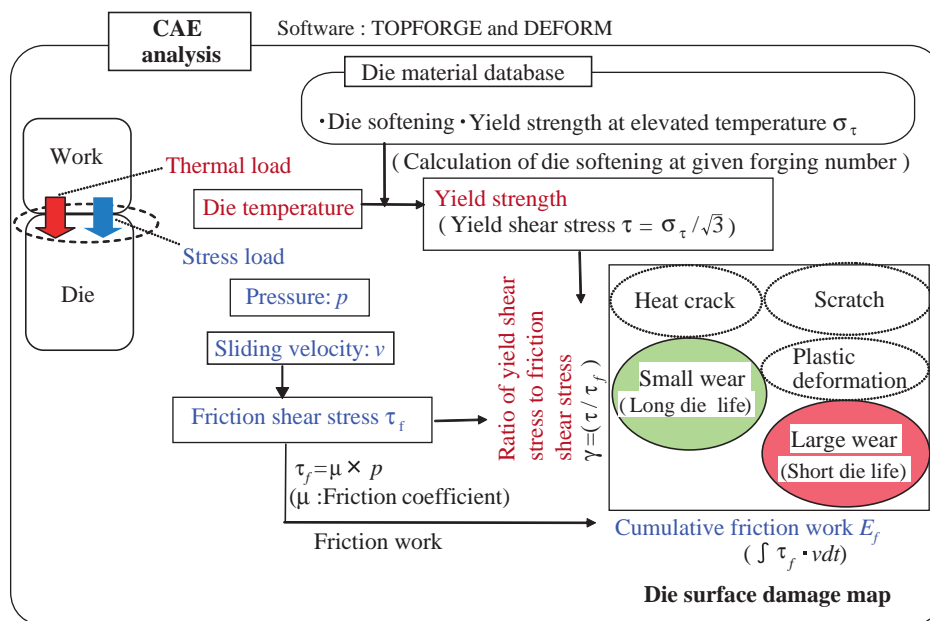


Fig. 1 Flow of judgment for die damage modes.

developed a new wear model.

The degree of wear was examined with the axisymmetric hot forging die shown in **Fig. 2**. It was found that the amount of wear can be expressed by Eq. (1).

$$W = (N - N_c) w \dots \dots \dots (1)$$

Where W is the total amount of wear at forging number N , N_c is the forging number at which the die begins to wear out, and w is the amount of wear produced by each forging cycle after N_c .

N_c is determined using Eq. (2). When the yield strength of the die at an elevated temperature just satisfies Eq. (2), the corresponding number of forging cycles is defined as N_c .

$$\gamma = (\sigma_\tau / \sqrt{3}) / \tau_f = 1 \dots \dots \dots (2)$$

Where σ_τ is the yield strength of the die material at the elevated temperature, and τ_f is the shear stress of friction.

w is given by Eq. (3).

$$w = C (E_f)^a / (\sigma_\tau)^b \dots \dots \dots (3)$$

Where C , a , and b are constants, and E_f (cumulative friction work) is given by Eq. (4).

$$E_f = \int \mu p \cdot v dt \dots \dots \dots (4)$$

Where μ is the friction coefficient, p is the pressure, and v is the sliding velocity.

Before the cooling model was established as shown in **Fig. 3**, the temperature rise of the die was calculated by varying the base temperature in the steady state from 100 °C to 300 °C while considering the heat transfer and the heat generation during forging. The temperature of a die during cooling was obtained by a linear approximation method. The hardness of the softened die was calculated by integrating the value of one temperature waveform in the steady state along the forging number of cycles, whereas the value of one temperature waveform was computed using the tempering parameter, λ^5 given in Fig. 3.

2.2 Predicted wear values

The constants of the wear equation were obtained by applying regression analyses to the degree of wear and analytical load values at four different locations on the No. 1 die.⁶⁾ A comparison of the measured and calculated amounts of wear, for given numbers of forging cycles and four different dies, is

illustrated in **Fig. 4**, along with the wear equation. For all the four dies that we examined, although there is a maximum gap of about 0.2 mm between the calculated and measured values of N_c and w , the

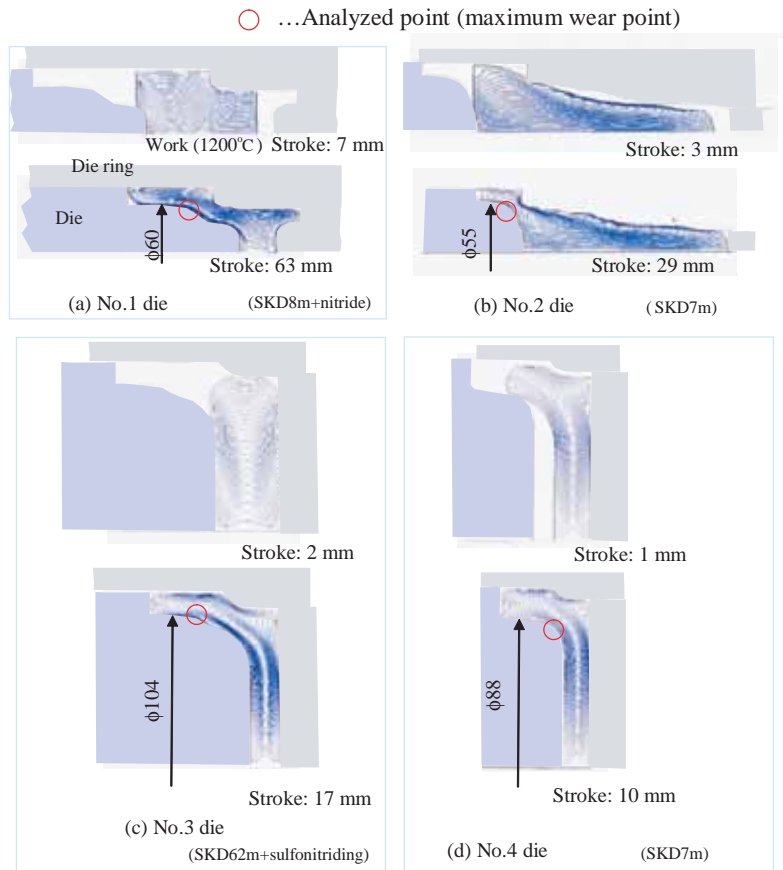


Fig. 2 Practical dies and analyzed points for wear analyses.

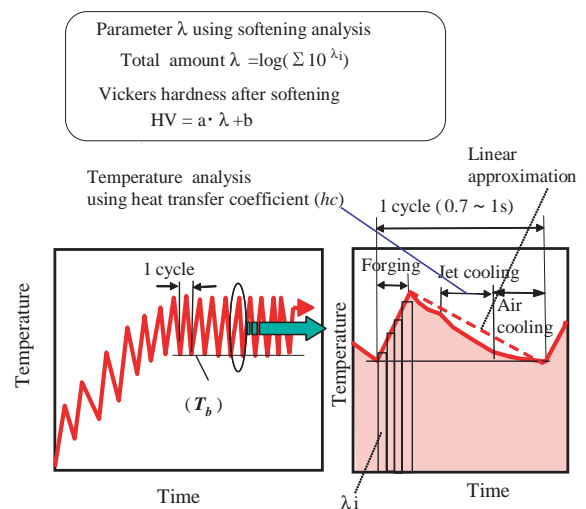


Fig. 3 Repeated calculation of model temperature change and hardness of die during forging.

tendencies of the die lives appear to be in good agreement.

A feature of the present wear equation is that the amount of wear at an arbitrary point on a die can be calculated, thus making it possible to obtain the distribution of the amount of wear over the surface of a die.

3. Prediction of die temperature

3.1 Cooling model

The lubricant jet conditions for mass production dies were expressed in terms of the Reynolds number and reproduced with the experimental jet model illustrated in **Fig. 5**. The Reynolds number (Re) is expressed by Eq. (5).

$$Re = D V / \nu \dots \dots \dots (5)$$

Where D is the diameter of the jet nozzle, V is the velocity of the jet at the nozzle exit, and ν is the kinematic viscosity.

3.2 Measuring the cooling ability of a jet

The jet perpendicular to the surface of the die was taken as the standard case to be discussed. The effect of the distance from the jet striking point on the heat transfer coefficient was also investigated.

Thermal analyses of the jet cooling model were carried out using commercial software, MARC, for a variety of heat transfer coefficients on the surfaces of the die. The correct heat transfer coefficients for different cooling conditions were determined by comparing the calculated and measured temperatures 1 second after the start of the jet at a position 0.5

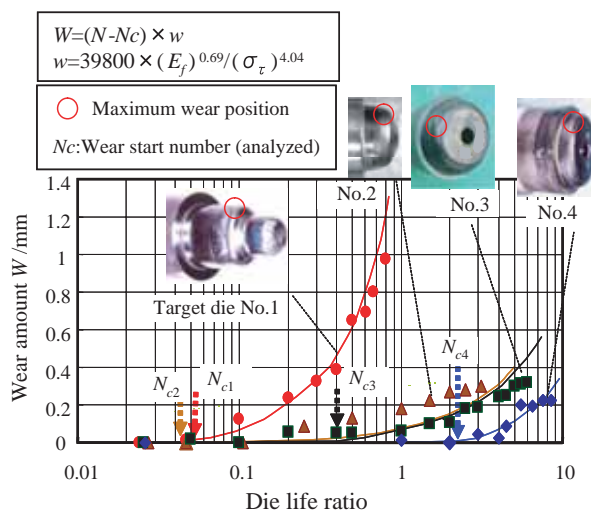


Fig. 4 Predicted and measured wear amount.

mm below the surface of the die.

3.3 Measured jet cooling ability results

An example of a measured cooling curve and the corresponding heat transfer coefficient, as determined by the above method, are illustrated in **Fig. 6(a)**, together with the experimental conditions, where water at 25 °C (acting as a lubricant) was sprayed onto the model die which was preheated to 300 °C. The temperature measured 1 second after the start of the jet was used to determine the heat transfer coefficient to ensure a steady heat transfer state and thus obtain the heat transfer coefficient in a short time. If, therefore, the results are arranged as shown in Fig. 6(b), the heat transfer coefficient can be acquired immediately for any given cooling condition.

In this research, we noticed that the distance from the jet striking point and the die temperature had relatively little effect on the heat transfer coefficient.

The cooling abilities of different nozzle diameters

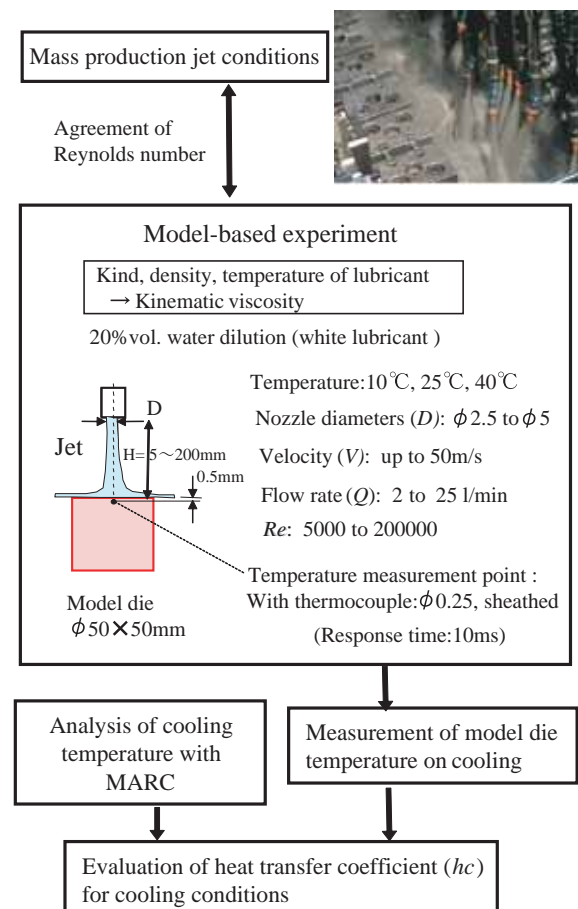


Fig. 5 Evaluation of heat transfer coefficient (h_c) for cooling conditions.

were arranged in terms of their Reynolds numbers and flow rates, as illustrated in **Fig. 7**. It is obvious that the cooling abilities are expressed well by the Reynolds numbers, but not by the flow rate when the nozzle diameter changes.

The relationship between the heat transfer coefficients and the Reynolds numbers is summarized in **Fig. 8** for all the investigated cooling conditions, which also include the different kinds, and temperatures, of lubricants. From Fig. 8, it can be seen that there is a good correspondence between the heat transfer coefficients and the Reynolds numbers. When the temperature of the lubricant was changed, the heat transfer coefficients were no longer related to the flow rate due to the change in the kinematic viscosity.

The surfaces of dies were classified into two basic shapes: plane and curved. For these two different

types, the difference in the relationship between the heat transfer coefficients and the distance from the jet striking point was also examined. The results are shown in **Fig. 9**. At the jet striking point, the heat transfer coefficient for the curved surface was greater than that for the plane surface. With the increase of the distance from the jet striking point, the heat transfer coefficient for the curved surface decreased rapidly, while that for the plane surface decreased slowly. The effect of the inclination angle of the jet from the perpendicular direction was also investigated and it was found that the heat transfer coefficient tended to increase together with the inclination angle.⁷⁾

4. System for predicting the temperature and wear amount of dies

The prediction system was constructed according

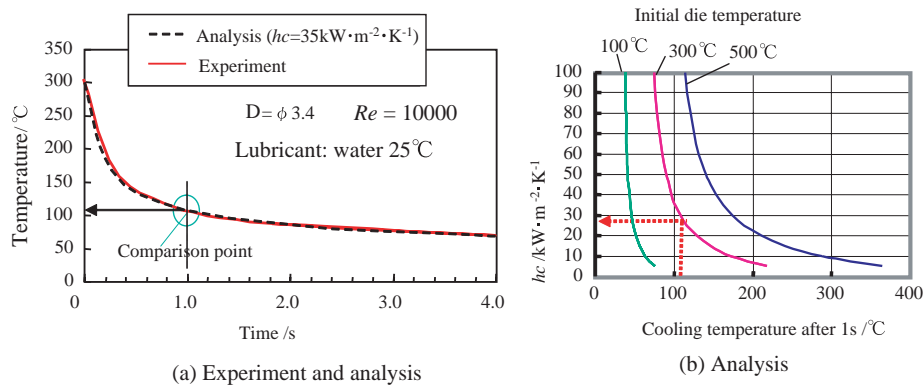


Fig. 6 Example of cooling temperature model test and analysis for the determining heat transfer coefficient (hc).

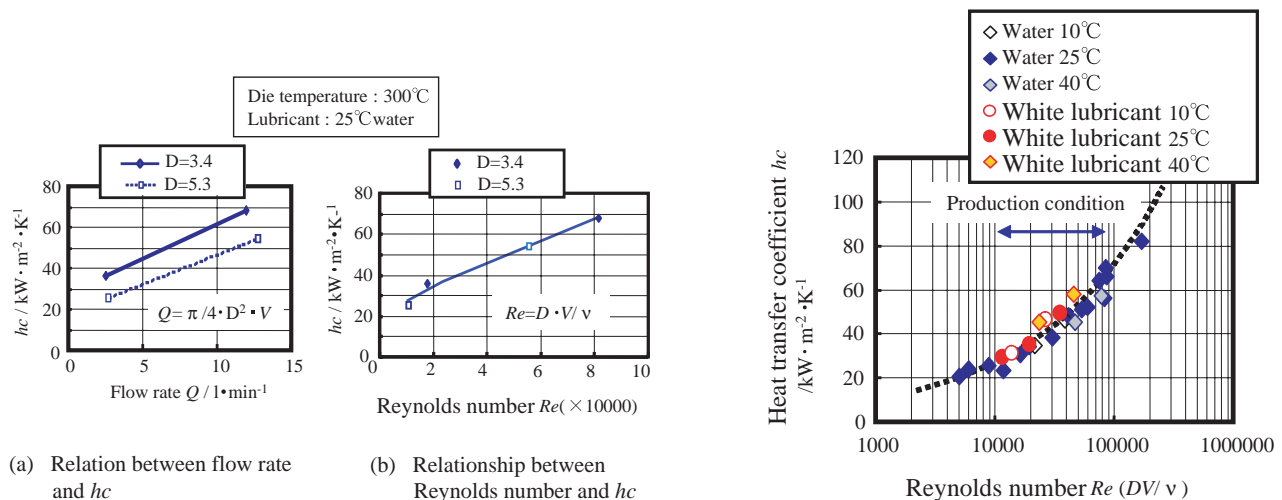


Fig. 7 Comparison of Reynolds numbers and flow rates for determining cooling abilities.

Fig. 8 Relationship between Reynolds numbers and heat transfer coefficients.

to the flow chart shown in **Fig. 10**. The temperature and the amount of wear in the dies could be predicted successfully under a range of cooling conditions during the process design stage.

With the aid of the present system, it is not only possible for us to predict the temperature and life of dies under the current production conditions, but we can also determine the design of optimum cooling

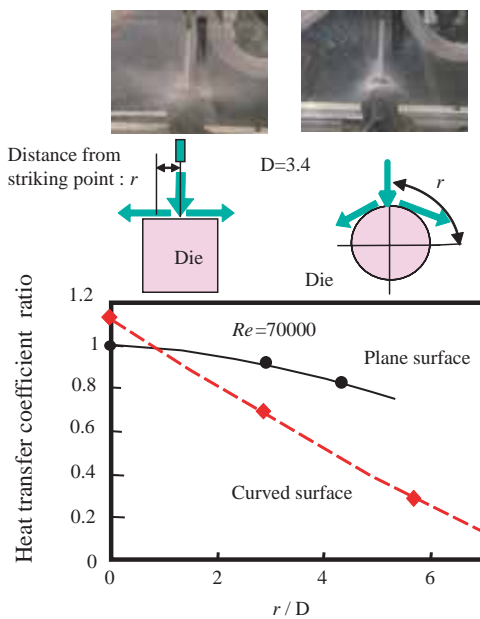


Fig. 9 Change in cooling ability with distance from jet striking point and die shape.

conditions for extending the die life. Therefore, we should be able to reduce the amount and duration of trial production, as well as the costs incurred for dies.

5. Conclusions

A new CAE system was developed that can be used for predicting the amount of wear and the temperature of dies under the influence of a jet cooling system in the process design stage. The results of this research are summarized as follows.

(1) An equation defining the amount of wear in the forging dies was constructed based on the amount of friction work imposed acting on the surfaces of the dies and the yield strength of the softened dies caused by repeated processing. The proposed equation proved to be useful for the design of hot forging processes.

(2) The cooling abilities of a range of cooling conditions involving different die and lubricant temperatures were expressed in terms of the corresponding Reynolds numbers, in which the temperature dependence of the kinematic viscosity was also considered.

(3) It proved possible to design the cooling conditions for an expected control target of die temperature and die life.

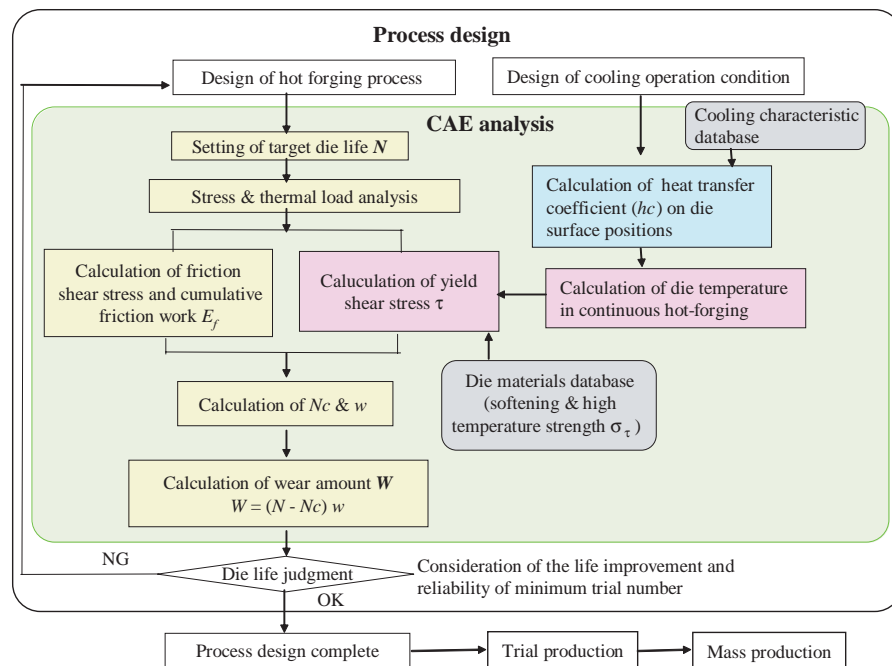


Fig. 10 Flow of the temperature and wear life prediction of a hot-forging die.

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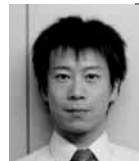
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