Review

Trend in Process Tribology Focusing on Die Life -Key Technology for Precise and Efficient Production-

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Abstract

There has been a growing demand on the production lines to produce high quality products at low cost while considering the global environment. Process tribology is one of the key technologies to fulfill this demand. Process tribology that covers tribology related to metal forming technology is widely discussed from the basic theory to technology evaluation and application. This paper discusses its current state and the trend mainly from the standpoint of improving die life. It evaluates the role of tribology in the process, states the positioning of the test method to evaluate the characteristics of tribology followed by the introduction of applications. The paper then describes the objectives of process tribology, which includes the improvement of forming limits and die life as well as saving energy. It also discusses the cautions for exploiting the characteristics of die and surface treatment to the most effective level and new trends in lubricating technology. With regard to the improvement of die life, the paper proposes (1) establishing a life determining standard, (2) observing damage, (3) discussing causes of damage, (4) eliminating unexpected phenomena, (5) taking measures concerning the process, and (6) steps for changing die materials and lubricants. It refers to the importance of developing on organization for covering process tribology and human resources. Furthermore, it summarizes the present state of die load estimation using simulation and the technology of predicting die life as the future direction of the study.

Keywords: Process tribology, Maintenance tribology, Die and mold, Tribo-simulator, Die life, Lubrication, Prediction of die life, Mechanical and thermal load

1. Introduction

In recent years, the protection of the global environment is socially demanded while economic growth is simultaneously desired. In the automobile manufacturing industry, the improvement of fuel economy is directly connected to CO_2 reduction and related technologies are being seriously developed. To realize a high fuel economy, reducing the friction of sliding parts and the vehicle weight are effective. To reduce friction, it is important to provide the optimal combination of lubricant and material while preventing unnecessary friction from being generated by raising parts precision. This depends on how precisely the metal forming can be improved in the production stage. On the other hand, the compatibility of reduced vehicle weight and safety is essential. This requires the appropriate distribution of structural strength, so aluminum and titanium alloys and high tensile steel are being increasingly adopted. To retain durability and designability, stainless steel is also being used. Being hard to form, these materials easily seize, have greater forming loads, and thus exert a heavier load on the die.

In relation to global environmental protection, energy-savings, high efficiency production and CO_2 reduction are required for the production process. With regards to protecting the working environment, the reduction of graphite-based lubricants is strongly demanded. The use of oil is being positively reduced in consideration of the surrounding environment.[1] Under these circumstances, the production of precision, high-quality products inevitably increases the importance of applying tribology to the forming process.

This paper focuses on the dies, which are indispensable in the forming process. It summarizes how process tribology is presently being used to efficiently produce high-quality products and how it will develop in the future. It also touches on the concept of tribology with respect to the damage and life of dies used for metal forming.

2. Role of tribology in the metal forming process

Process tribology mainly concerns friction, lubrication and wear during the metal forming processing where four elements of die, work, lubricant and external conditions are considered. Regarding the friction between the work and the die, macroscopic plastic deformation of the work makes process tribology different from that of the mechanical elements. The concept of process tribology is mainly applied to two production fields. One is energy reduction in the production equipment and the other is improvement of the surface quality of the products and their precision.

As an example of the former, the reduction of rolling power through the use of lubricants is known. With respect to the motive power energies of rolling machines, friction energy occupies 40 to 60%.[2] As **Fig. 1** shows, a case is reported where the adoption of a lubricant reduced the rolling load by about 30%.[3] Energy saving is promoted by establishing appropriate lubricating conditions.

As an example of the latter, **Table 1** indicates the role of lubrication in metal forming. Lubrication is mainly aimed at reducing the friction and the controlling the reaction between the work and the die material. As a result, damage is prevented and high-quality products are produced. In the cutting process, tribology is applied to the cooling of the tools and preventing a reduction in the cutting force and adhesion. Tribology in the casting process is a little different from normal tribology because of contact between the die and molten metal. The concept of tribology is reflected when studying the heat insulation of the die coating agent for heat checking[4] or giving consideration to the pick-up behavior during die release.[5-10] Moreover, in powder metallurgy, the effects from lubrication on the filling and compacting behavior of powders become important in association with the green density.

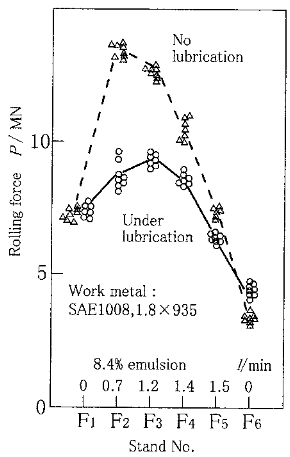

Fig. 1 Effect of lubrication on reducing rolling force of each stand of hot rolling.

3. Evaluation test of tribo-characteristics

3. 1 Positioning of evaluation test

When considering the tribological characteristics in metal forming, different evaluation stances are taken depending on whether we are forecasting the characteristics in the design and trial phases or trying to acquire measures to improve the service

Table 1 Role of lubricant in metal forming.

1. Reduction in friction
2. Improvement of surface quality of products
3. Protection against seizure and tool wear
4. Increase in releasability of products from die
5. Insulation from heat
6. Cooling die
7. Protection for oxidation of work metal
Needs for lubricant
easily remove, easily maintenance
anti-oxidation, good wettability to die

life of dies. In other words, it is the difference between whether we discuss the behavior in a one-time forming test or the changes in behavior in repetitive tests. **Table 2** summarizes these differences.[11)]

In the evaluation test for the former, the level of effects will be examined under predicted conditional factors. The conditional factors will be specified in advance and their characteristics will be examined by a parameter study. This will guarantee product quality. The die material or lubricant is selected and the result is reflected in the processing condition and/or process design. In other words, the evaluation test in this case can be positioned as the test for determining the limit of the tribological characteristics.

In the case of the latter, however, the product life factors are predicted on the basis of dies that actually came to their the end of their service life. The test is conducted to examine the measures needed for improving the life. In this case, the test conditions are set up close to the actual forming conditions, temperature and atmosphere. The number of tests are determined close to the actual production. In other words, this test is used to determine the changes in the tribological characteristics with elapsed time. Thus it is positioned as an evaluation test for verifying the tribological characteristics in the production phase.

On the other hand, there is a common view on how to position the test toward the evaluation object. **Figure 2** clearly expresses this view.[12)]

When confronted with the task of improving the product quality or die life, we are apt to attempt to obtain the direct "output" by only giving the "conditional factors", as shown by Path A in Fig. 2. On the other hand, Path B is not practical as it is quite difficult to obtain a result by leading to the mechanism after solving the complex and various conditional factors. As a result, Path C is considered as the third path. In other words, this is the path for obtaining the "result" based on the evaluation results after mapping out an appropriate test method. The test referred to here is not the "measuring method" for obtaining the mechanical properties using a material tester. It is the test method for examining how this method helps solve the problem while thinking about the mechanism of the object phenomenon. In this connection, it becomes necessary for the "test method" and the "mechanism" to be repeatedly changed (Path D). Instead of the repeating the trials and errors on Path A, the seemingly circuitous Paths C+D get us to the "results" faster.

3. 2 Evaluation test method

One of the characteristics of friction in metal forming is that macroscopic plastic deformation occurs on one side of the material. Accordingly, the surface area of the material may change, mostly by expanding. Newly developed surfaces are easily exposed, simultaneously causing the microscopic surface structure to change. A temperature rise also occurs due to frictional heat generation and plastic deformation. In addition, the above changes affect the behavior of the lubricant that plays a major role in determining the state of friction between the die

Table 2 Two types of tribo-simulator for metal forming.

type	single operation type	multi-operation type
purpose of evaluation	severity of forming conditions ex. critical working reduction to seizure	cumulative phenomenon ex. generation and growth of seizure
similarity in material test	tensile test	fatigue test
object of study	non-stationary phenomenon	stationary phenomenon
application	for development (research & development, production technology)	for improvement (production line, workshop)
examples	・backward extrusion test ・ball penetration test ・taper plug penetration test ・drawbead test	・intermittent compression - twist test ・draw type sliding test ・U-shape bending test ・shearing type test

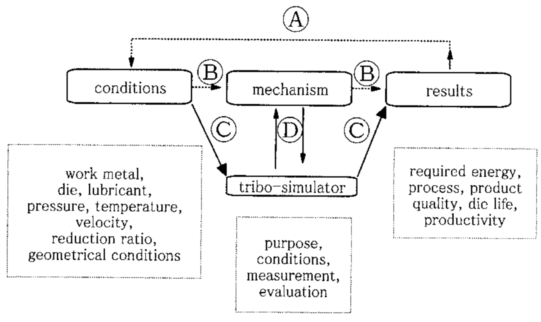

Fig. 2 Role of tribo-simulator in process-tribology system.

and the material. In other words, the amount of oil that determines the oil film thickness on the surface, and its introduction to the surface, trapping and other behaviors vary depending on the forming method and/or conditions. It is quite difficult to incorporate all of these characteristics of metal forming into the test method. It is desirable that the frictional and normal forces be measured and that the test conditions be changed to cover a wide range.[13)]

Various test methods have been developed according to the objective of the evaluation.[13, 14)] Recently, the Journal of the Japan Society for Technology of Plasticity published an article on the evaluation method.[15)] According to the above summary, the test method is classified into three categories, namely, the general-purpose basic friction test method, the basic friction test method for metal forming and the model friction test method for metal forming. Typical examples of the general-purpose basic friction test method are the four-ball test and the pin on disk test. These test methods are used for evaluating the state of friction on the sliding surfaces of bearings and other mechanical elements. When using these test methods, it is necessary to fully examine to what extent the lubricating state of the subject forming method can be reflected.

The basic friction test method for metal forming has a characteristic that at least one side of the friction pair is plastically deformed and is devised to produce data meeting the evaluation purpose by adopting a simple contact surface system.

The model friction test method for metal forming has an identical contact form modeled after or close to the actual metal forming or part thereof. It is designed to provide evaluation under test conditions similar to the forming conditions. It has a drawing, an extruding, a rolling type, etc.

3. 3 Application of evaluation test

For general examinations, the tests are used to obtain the expansion of the surface area in backward extrusion,[16)] examine the effects of carbide intervals on the generation of seizure[17)] and evaluate the compatibility between tools and works.[18, 19)]

On the other hand, for evaluating the applications, the mode of application differs according to the positioning of the evaluation test as stated in **Section 3. 1**. In the case of a behavioral evaluation test with a single forming, evaluation of the lubrication performance of B_2O_3 is done using the backward extrusion test,[20)] development of lubricant using the Ball Penetration Test[21)] and formability using the spike test, by which a conical testpiece is pushed in.[22)] In the repetitive behavioral evaluation, including the long running test, trials are conducted to evaluate the seizure performance of the aluminum alloy sheeting using the drawing-type friction test and to determine the softening behavior of hot forging die.

4. Application and development of process tribology

4. 1 Determining the forming limit and improvement

In press forming, an increased number of parts are formed using a thick sheet steel combined with cold forging.[25)] This method is characterized by a good yield and the forming of sectional parts with different wall thicknesses. Due to the higher load compared with conventional press forming, however, care should be taken when selecting the die material and lubricant. In addition, it is desired to have a steel sheet developed with compatibility for formability and strength.

Nonoyama et al. formed a deep hole having a polygonal section of approximately $12 \times 42 \times 53$mm depth in hard spring steel to evaluate the performance of a warm lubricant on a glass system using the backward extrusion test[20)] and devise a lubricating method, etc.[26)] Isogawa et al. used the spike test to evaluate the lubricant for the warm forging of stainless steel and the wear of tools.[27)] As the net shape forming of forged parts advances in the future, a number of products will approach the limit of forming, thus requiring a new evaluation test method to be developed.

4. 2 Improvement of die life

Figure 3 shows the possible damage to metal forming dies and the associated die material characteristics.[28)] To improve the die by reducing wear, galling (seizure), permanent deformation, plastic flow and heat check, it is necessary to consider the characteristics of the die, such as high temperature strength, oxidation resistance, thermal fatigue resistance and other material characteristics, along with compatibility with the work material.

Of course, theorefically considering the tribo-characteristics would not solve the problem since, for example, the wear of a cold forged die and that of a hot forged die have different characteristics. In addition, actual dies normally suffer damage in combination, requiring a balance to be kept among differing material characteristics. Regarding the improvement of die life, shortsighted replacement with a high performance die material or lubricant is often studied. It is necessary to make rational improvement by understanding the damage history to the end of the life and drawing an inference on the mechanism of the life cycle.

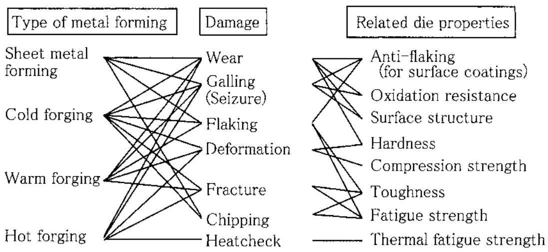

Fig. 3 Relationships between die damage and properties.

Figure 4 shows an example of how to improve the die life. First, step 1 is to clarify the criteria of the die life. It may be judged from degradation of the product quality compared with a set standard. However, the measures may differ depending on whether the criterion is appearance, precision or strength. Step 2 is to then predict the cause of life by observing damage to the die that causes quality degradation. Next, step 3 is to think mostly about the cause of damage that would most effectively increase the life. Step 4 is to then specify the cause of damage and step 6 is to take the necessary measures. However, it is necessary as step 5 to determine if such damage is specifically generated or in the ordinary state. In the example given in Fig. 4, these steps will ultimately proceed to selection of the die material. During the course of planning, operation procedures and lubricants will be studied.

In step 2, it is important to arrange the observation results with quantitative values as much as possible and develop them into a database. For example, regarding the die, examination and records should be

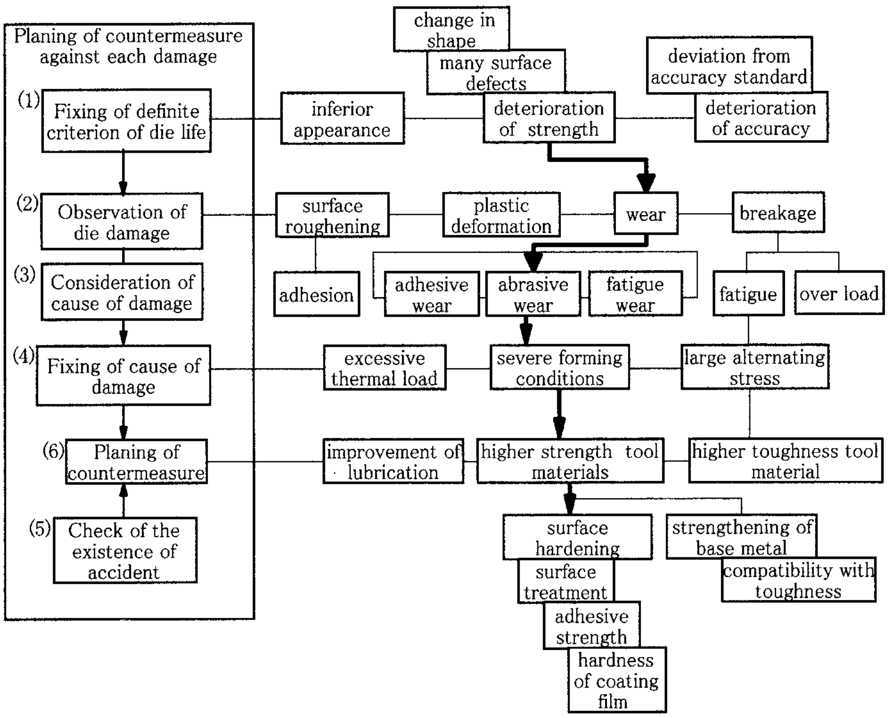

Fig. 4 An example of flow chart for improving die life.

made on the depth, area and location of wear and seizure, hardness of the die surface and changes in the surface residual stress, etc. Regarding the products, examination and records should cover the location, direction and the volume of seizure, and regarding the processing conditions, the processing load and temperature, die temperature, quantity of lubricant and lubrication piping trouble.

When estimating the cause of die life, it is important not to be misled by the keywords. For example, the expression that “life span is the result of die wear” only means that the die surface changes the position to the negative side from the initial shape. This thinking does not sufficiently describe the cause of die life. It is necessary to give thought to a model leading to damage. For example, it is necessary to think about whether the change to the negative side was caused by the die material, which was transferred to the outside or which merely changed the location by metal flowing. Also if the die material was transferred, whether it was little by little or in terms of a certain size, and so forth. Repetition of such thinking will ultimately enable a model to be developed in which the tool gradually softens under the thermal stress of the forming load, leading to deformation under the forming force and have cracks being generated as the strain increases. The cracks are then oxidized, become brittle and give way to greater cracks until multiple cracks merge together and peel off, or the material is separated from the die surface. Conversely, the model may represent a case where a sufficient lubricating effect causes repetition of thermal strain due to greater temperature fluctuation rather than by thermal softening of the die. This causes cracks to occur due to fatigue, ultimately leading to wear. If wear originates from the same crack, measures in these two cases should be reversed.

To determine the cause of damage in step 5, it is recommended that records of die life fluctuation be kept on the daily check sheet of the process. One of the ways is to use FMEA (Failure Mode and Effect Analysis)[29] of the process. These steps enable the minimum die life to be raised to the mean level.

On the other hand, to improve die life that has already reached the mean level requires additional processing. This is because there is only a small degree of freedom available when changing the processing condition because the process has been operating following the historical procedures and priority is given to retaining product quality. In this case, it may be effective to examine the situation using PDPC (Process Decision Program Chart),[30] which is frequently applied in TQC activities. This is because cooperation can be obtained from respective departments in the plant, production engineering and research and development for mutual communication and better understanding during the course of examination. The measures should be taken only when the above-mentioned analyses are completed (step 6). Naturally, the most effective points of improvement will be discussed, but it is better to first examine the improvement measures for reducing the die load conditions in the operation and when processing. Subsequent measures should be recorded and stored in a database and hopefully inherited as new technology. After implementing this step, check the effects. When the life improving effects become stable, proceed to changing the die material, surface treatment and/or lubricant. Changing these should be the final steps taken. It will then be possible to clearly understand the effects brought about by the change in the lubricant and/or die material, making it easier to determine their limitation and whether or not to develop other dies. It is difficult to verify the effects by merely changing the die material without studying the operation and process.

4. 3 Maintenance tribology

Tribology associated with the maintenance of production equipment is called maintenance tribology. It is expected to play an important role in future environmental measures. This section introduces an example of an iron work that demonstrated significant energy-saving and economical effects through the comprehensive use of maintenance tribology.[31] This foundry achieved direct economic effects of over 2 billion yen a year (during 1985) through the reduced use of lubricants, control of property degradation, development of diagnostic technology for lubrication abnormalities and new lubricant developing activities. It reduced the number of accidents to 1/10 during a five-year period. This example shows just how much comprehensive maintenance tribology, not merely the analysis of faults, can raise production efficiency. Naturally, in forging and pressing, tribology produces major effects in reducing working fluids and forming oils. The idea of tribology may well be incorporated on actual production lines.

Maintenance is thought less of than development and/or production. There is almost no department specifically devoted to improving die life. It is absolutely necessary to establish a system that routinely implements such activities that directly contribute to not only the economic effects but also energy-saving and environmental protection.

On the other hand, it is necessary for the personnel in charge of life improvement activities to acquire basic knowledge concerning tool materials, surface treatment and lubricants in addition to having knowledge of metal forming. In particular, knowledge of the types of tool steels and characteristics and changes in metal structures by heat treatment would be quite useful in observing die damage and predicting its mechanism. This would also streamline efforts toward die life improvement. Moreover, it will be necessary to correct the tendency to leave the matter to tool material manufacturers and lubricant makers. There is no tribo-characteristic evaluation test that is better than knowledge and discussion.

4. 4 Appropriate use of tool material and surface treatment

Many dies are made of so-called tool steel. Its characteristics are determined by quenching and tempering, and JIS standards establish the conditions. These conditions, however, are not absolute. Tool steel is treated under non-standard conditions according to the use and characteristics required. For example, when providing surface treatment at a later process, high-temperature tempering may be conducted on cold die steel. Or when using high-speed tool steel for cold forging dies, toughness will be improved if hardened at a lower temperature than the ordinary hardening temperature by about 80°C.[32] Either case is the result of giving importance to the toughness, and these methods are effective measures against large cracks. Regarding the selection giving importance to seizure resistance, it is recommended that the heat treatment condition be selected that precipitates many carbides as shown in **Fig. 5**.[33] In either case, care should be taken so that the characteristics are not only determined by hardness.

To improve the wear and seizure resistance, a hard surface coating is often provided. VC, TiC, TiN and other carbide and nitride films produce effects as they have better seizure resistance than the effects based on their hardness.[34] Care should be taken, however, against adhesion and surface roughness as these conditions hamper good original properties. Regarding adhesion, it is largely affected by the surface treatment temperature. Generally, higher adhesion is generated by CVD (Chemical Vapor Deposition) or TRD (Thermo-Reactive diffusion and Deposition) treatment than PVD (Physical Vapor Deposition) implemented from 400°C to 500°C.[35] On the other hand, if the surface roughness of the hard coating is significant, protrusions cut the work material mechanically or the surface irregularity becomes the starting point for seizure as shown in **Fig. 6**. The coatings then fail to provide seizure resistance as they originally should.[36] This point requires caution when surveying the coating characteristics or making an evaluation test.

Ceramics excel in wear and seizure resistance but they are brittle, hence, they are not usually applied to dies for metal forming. There is a good example, however, of having used sialon for an extrusion die.[37] That is, hot die steel was shrink-fitted around the outside periphery to prevent tensile stress from

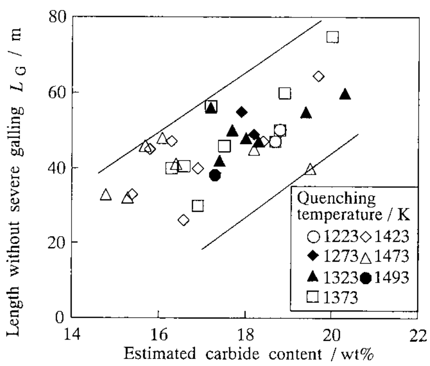

Fig. 5 Change in limit of drawing length without severe galling with carbide amount in high speed tool steel.

being generated, thus preventing cracking. This suggests the future direction of material development in that combined materials were advantageously used.

On the other hand, applications technology of die material matched to production and new materials are being developed for press dies to reduce cost.[38] This is another direction for future material development.

4. 5 New development of lubrication technology

In hot strip rolling, the use of lubricants is increasing along with the recent adoption of high-speed steel rolling. For the caliber rolling of stainless steel, which requires very severe friction conditions, a calcium-added lubricant has been developed and effectively applied to reduce product surface damage and the task described in the following process.[39]

In cold forging, die life has reached an almost satisfactory level as the result of chemical conversion coating of the material and hard coating of the die. To further reduce the cost, a short-time conversion coating was invented and a water-soluble lubricant was developed to enable re-treatment midway through the processing. In addition, special lubricants for die lubrication have been developed for both ordinary[21] and stainless steels.

In the future, with the growing demand for high-precision forming, lubricants having excellent characteristics will be continuously demanded. At the same time, they will be reviewed from the viewpoints of cost, washability, waste-disposability, etc.

Also, from the viewpoint of environmental protection, various tests are being conducted on press forming. Lubrication using ice[41] and frost[42] generated from the cooling of the die is being developed in addition to lubrication under water pressure[43] and lubrication using a scattered solid lubricant with the water serving as the carrier.[44] Other studies are being made to develop a lubricant that uses water with suspended wheat flour for forming titanium and stainless steel sheeting.[45] The development of non-petroleum-type lubricants may be further explored if at some sacrifice to lubricating performance or cost.

In warm and hot forging, graphite-based lubricants have been frequently used. The changeover to a white lubricant is increasing in order to improve the working environment and waste water treatment.

4. 6 Estimation of die load

In studying die life, it is very important to know the external conditions of the stress and thermal load. It is not easy, however, to obtain these data during the production process. If various data are obtained through the aforementioned evaluation test methods, such data could not be utilized unless the load condition is known in the actual processing.

Attempts are being made to fill this gap. Saiki et al.[46, 47] developed a test device for estimating thermal load. They estimated the temperature rise on the die surface using a numerical simulation. Accordingly, they have begun a study to forecast die life attributable to softening.

Regarding stress estimation, Hansen et al.[48] developed a test method to measure the variation in surface pressure and friction force during forming. Changes in the coefficient of friction are determined by this method. To enable the application of a numerical simulation, which has become popular and is being adopted lately, a sheet metal forming friction test method has been developed to measure the effects of various forming parameters (sliding velocity, strain rate, distortion, etc.) on friction.[49]

4. 7 Forecasting die life

Improvement of die life itself is important as it is effective in raising production efficiency. It would be significant if it were further developed to the level at which die life could be forecast. Forecasting means that a die life model is constructed and quantified. As it is to be combined with the

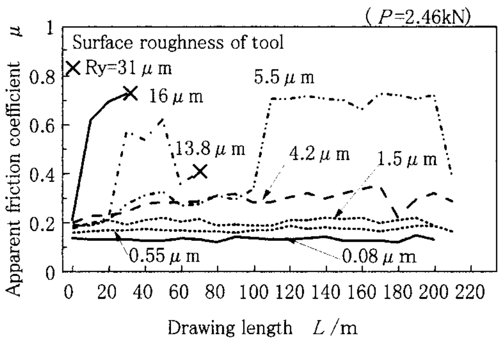

Fig. 6 Relationships between friction coefficients and drawing length for different surface roughness of VC coated tool.

numerical simulation, it would become possible to feed back data for designing the process and die. Thus, die life can be included at the design stage so that the process and die structure can be optimized.

To develop friction and seizure phenomena into a model is not simple because of the number of factors involved, which mutually affect one another. With regard to the friction of mechanical elements, the methodologies for retaining functions,[50)] the zero wear and measurable wear concept[51)] have been proposed with the indication of a wear map.[52)] Presently, the proposed forecasting technology in process tribology is mainly based on forecasting material fatigue.[53-55)] Generally speaking, the fatigue strength of a high hardness die is greatly affected by non-metallic inclusions, which is difficult to control at the manufacturing stage of the material. It is not easy to improve the level of forecasting precision quantitatively enough to apply it to actual dies. It is also necessary to develop a life model based on factors other than fatigue. At present, it may be appropriate to find variations in the tribo-characteristics and thermal load caused by changes in the load condition and die form through parameter studies[56)] and apply the findings to study measures aimed at improving die life. In the future, it is expected that a technology will be established to examine die life in advance through the realization of three-dimensional simulation, high-speed operation, application of a neural network[57)] and the construction of models.

5. Conclusion

Of the four elements of process tribology, that is, the die, work material, lubricant and external conditions, the trend in technology mainly associated with the die has been summarized. Emphasis was placed on improving die life by utilizing the evaluation test, which might have resulted in treating other topics with less insight. The author wishes the reader to refer to the references for the basic theories, lubrication concepts and other contents not covered in this paper. He hopes that the complex tribo-phenomenon in the forming process will be clarified as phenomenological analysis and modeling advances are fused with numerical analysis in the future.

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