METHODOLOGY OF EVALUATION OF TOOL WEAR USING FINITE ELEMENT METHOD

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DOI : 10.17973/MMSJ.2016_11_2016133

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This paper describes options available for evaluating tool wear, focusing predominantly on closed-die forging. Correct design of tools and evaluation of tool wear have a substantial bearing on the final price of a product, which is why we have been dealing with this question, striving to develop an optimal methodology for tool evaluation. Wear can be evaluated using the finite element method. However, numerical computations must always be calibrated to the material and the process conditions in question.

KEYWORDS

tool wear, forming, closed die forging, forming tools, finite element method.

1 INTRODUCTION

Designing a tool for a forming process involves identifying not only the shape and functional surfaces but also a suitable material. The choice of the tool material and its heat treatment then dictates the price of the tool. For these reasons, information about the tool life is a valuable commodity.

Methods for predicting the life of a part are varied but most of them are experimental techniques. The disadvantage of experimental methods is that they are typically laboratory tests which are conducted under certain conditions. This means that the life assessment takes the form of general life prediction.

However, to explore wear, methods which can identify high-wear locations are needed. One available option involves field trials but these are time-consuming and expensive.

Another option is to predict wear using finite element method calculations. It is demanding in terms of input parameters but also more cost-effective and time-efficient. The problematic part of such numerical solutions is acquiring input parameters for wear calculations. These input values (such as the friction coefficient, heat transfer coefficient and failure parameters) must be obtained from tests. Such tests may involve laboratory tests, which have relatively narrow specializations, or adapted technological tests, which are more demanding but offer calibration for complex processes without the need for interpolation between laboratory and real-world conditions.

2 TECHNOLOGICAL TESTS

It is advisable to optimize input data for finite element modelling (e.g. friction coefficient and heat transfer coefficient) using information from technological tests [Kubik 2013]. Technological tests can be classified into laboratory and field tests. The main distinction between them lies in the test scope and in the controlled parameters. In laboratory tests, there are greater numbers of the latter, e.g. the forming temperature.

2.1 *Extrusion tests*

These tests are based on forcing punches into material. Their evaluation concerns the final shape of the billet (typically a cylindrical shape) at the end of the process which involves a considerable influence of friction on the material flow.

In one of their variants, a punch is forced into a cylindrical billet which is placed in a cavity and resting on a punch of identical geometry as the moving punch (Fig. 1). The amounts of material flow against the moving punch and against the stationary punch are evaluated. The lower the friction value is, the smaller is the difference between these flows. Under ideal frictionless conditions, the amounts of material flow against the moving punch and against the stationary punch would be identical. In this test, the primary quantity of interest is friction.

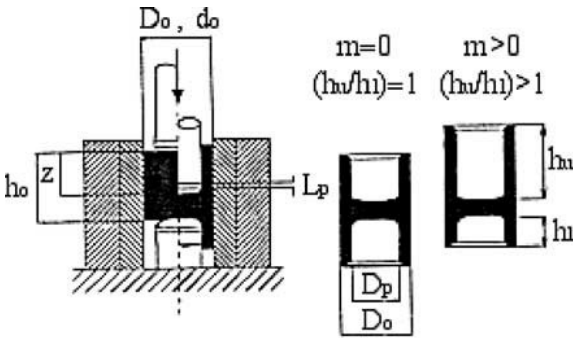

Figure 1. Friction test [Fereshteh-Saniee 2004]

Another variant comprises two lubricated styluses being forced into a heated specimen. Its principle is illustrated in Fig. 2. Using this test, the effects of friction can be determined. When this test is repeated, one can also evaluate wear in the styluses.

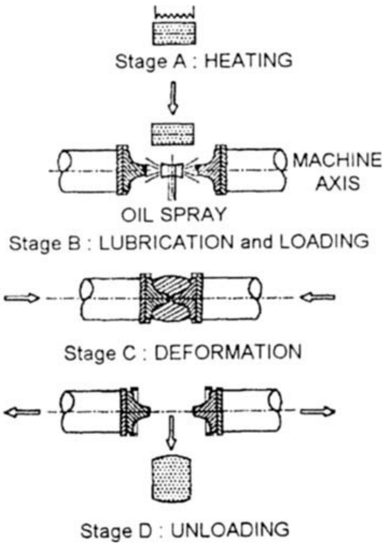

Figure 2. Friction test [Bariani 1996]

This arrangement is better suited for laboratory testing, given the specimen size and the associated requirements for testing conditions.

2.2 *Spike test*

This is a special upsetting test (Fig. 3), where the top die is provided with a conical impression. The billet size can be adapted to the testing machine.

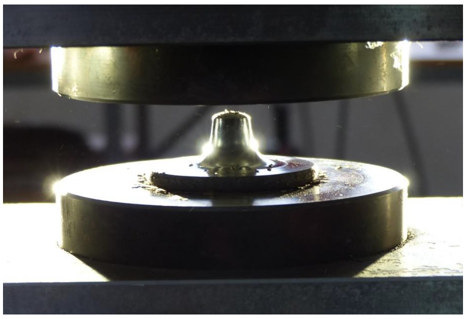

Figure 3. Spike test specimen after forging

With a correctly chosen shape, the final shape of the billet strongly depends on the friction coefficient. The readings which are compared include the resulting height and diameter.

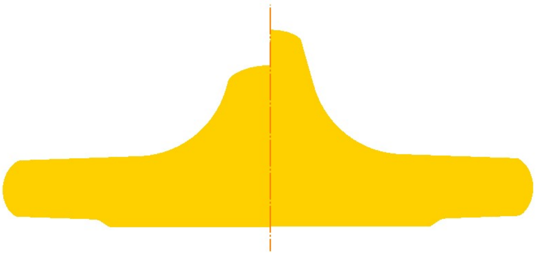

Figure 4. Resulting shape of spike test specimen found by numerical calculation with the use of various friction coefficient values: 0.1 left and 0.7 right

When repeated, this test can also be employed for evaluating wear in tools. In such case, lubrication is very important.

3 METHODOLOGY OF FINITE ELEMENT METHOD COMPUTATIONS

Wear predictions developed by means of the finite element method can be obtained using various methods, depending on the particular software employed. Our company uses DEFORM which offers two methods of predicting tool wear. Wear is calculated from contact conditions between two bodies.
In the post-processing stage, both total wear depth from a single process and time-dependent cumulative wear can be evaluated. The amount of wear is derived from the sliding velocity, contact pressure and the temperature at the contact location of the bodies. Post-processing allows these values to be evaluated independently.

Archard's model
[SFTC 2016]
This model is generally better suited for discrete processes such as cold or hot forging. In these cases, abrasive wear is the dominant wear mode.

$$W = \int K \frac{p^a \cdot v^b}{H^c} dt \qquad (1)$$

where: W = tool wear
p = interface pressure
v = sliding velocity
H = hardness of tool material
K, a, b, c = constants
dt = time increment

Usui's model
[SFTC 2016]
This model is generally better for continuous processes such as metal cutting, where diffusion is a major contributor to wear.

$$W = \int a \cdot p \cdot V \cdot e^{\frac{-b}{T}}\, dt \qquad (2)$$

where: W = tool wear
p = interface pressure
v = sliding velocity
T = interface temperature
a, b = constants
dt = time increment

Typically the coefficients used for these models should come from a series of calibration experiments. In lieu of calibrated data, standard values can be used to obtain relative wear rates for similar processes.

4 EXPERIMENT

In our company, we have developed a special technological test for evaluating wear. Its purpose was to map tool wear to the greatest extent possible. In this test, a die with a ridge is forced repeatedly into material. The shape of this ridge was designed to impose the most severe effect on the die material.

4.1 Technological test

In this proposed technological test, a die with two ridges was used, where each of these ridges had different properties. The die was made of an ordinary tool steel which is used for making dies and forging tools. One of the ridges was provided with a weld deposit for higher hardness.

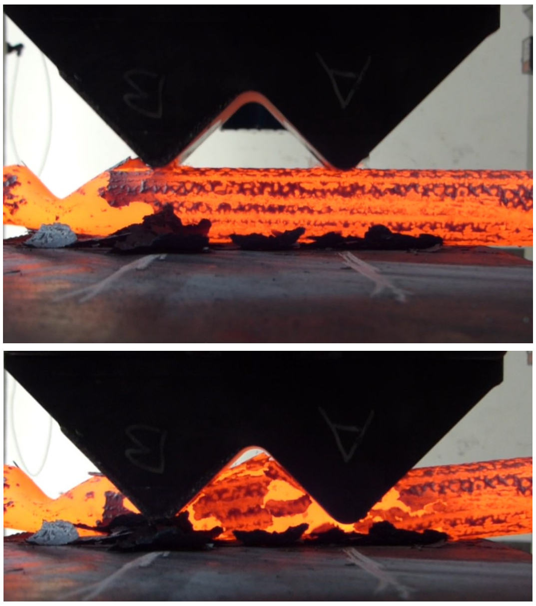

Figure 5. Progress of the technological test

Parameters of the technological test

- upper die – 60 mm width, 90° ridge angle, 90 mm distance between the ridges, R 10 mm ridge radius, 55 HRC and 62 HRC surface hardness of the ridges (base material and the clad ridge, respectively)
- flat lower die – 400 mm width

- billet – 40 mm diameter rod from S355 material heated to 1100 °C
- test parameters – 75% reduction of the initial diameter, 1000 repetitions

In order to obtain uniform wear in both ridges, the upper die was turned half-way through the test. The temperatures of both dies were measured and found to be in the range of 250–300 °C.

Evaluation of the technological test

The wear in the ridges caused by the test was evaluated using several methods. The primary evaluation method involved measuring the roughness of the surface prior to and after the test. It was carried out in the middle region of the ridge where the forming took place. The roughness reported here is a mean value from ten readings.

Table 1: Roughness of the plain ridge from the base material

Roughness	prior to testing	after testing
Ra [μm]	0.72	4.25
Rz [μm]	3.98	20.88

Table 2: Roughness of the clad ridge

Roughness	prior to testing	after testing
Ra [μm]	0.52	4.47
Rz [μm]	3.15	21.78

Another wear evaluation method was based on microscopic examination of the surface. The results showed that abrasive wear was caused by the technological test. This evaluation merely confirmed the outcome of the roughness measurement. In order to assess dimensional changes, two methods of measurement were used. The first measurement was carried out using a contact contour measuring instrument which offers an accuracy of down to ±1 μm.

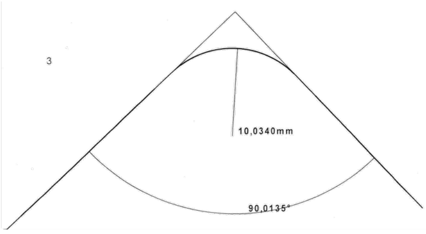

Figure 6. Unworn die ridge measured using a contour measuring instrument

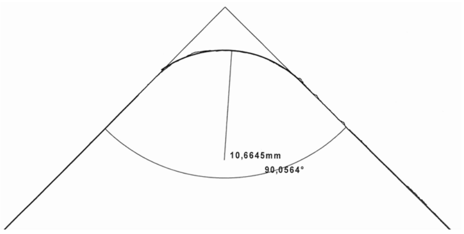

Figure 7. Tool steel ridge after technological test measured using a contour measuring instrument

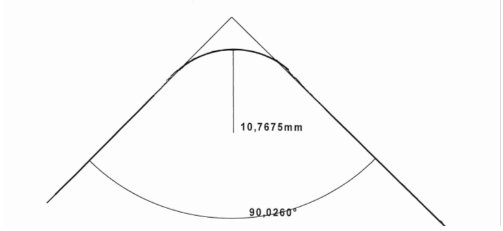

Figure 8. Clad ridge after technological test measured using a contour measuring instrument

The above figures show examples of measurement carried out using a contour measuring instrument. On each ridge, five profiles have been measured. Fig. 6 shows the ridge profile prior to the test. The profiles obtained from all ten measurements had identical shapes. Fig. 7 and 8 show the measured profile in the middle of the tool steel ridge and the clad ridge, respectively.

The wear in the ridge can be determined from the measured data. By comparing the arcs fitted to the unworn and worn ridges by means of the contour measuring instrument, one can determine the wear amount. Here, the average value was 0.7 mm. This method of measurement has a disadvantage in that a geometric shape must be fitted to the identified profile, and this shape is then measured. This procedure compromises the accuracy of the method. Another disadvantage is in that the measurement takes place at discrete points.

The other measurement method involved the use of the T-scan laser scanner. Its accuracy is poorer than in the previous case, ±20 μm, but its strength lies in providing a general view of the dimensions and surfaces of the part.

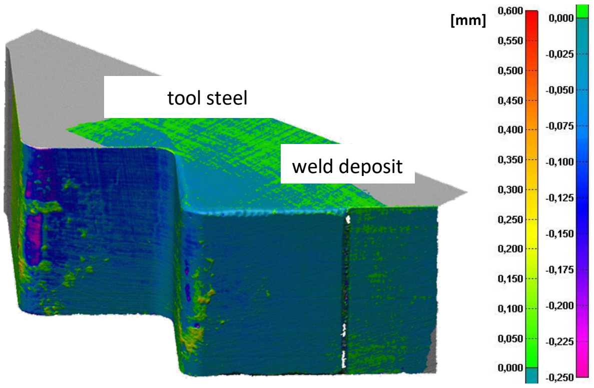

Figure 9. Measurement by means of laser scanner - (the scale was split into two parts for the sake of clarity)

Fig. 9 shows the results of the laser measurement. The die was scanned before and after the test. In this figure, the resulting virtual models are superposed and their shape deviations are highlighted using the colour scale. Positive values indicate the locations where the volume of the worn die rises above the volume of the unworn die. Negative values indicate the locations where the volume of the material is below the volume of the unworn die.

The results of laser scanning show that the maximum wear amount is 0.25 mm and that there are areas with scale sticking to the surface. The comparison between the two ridges suggests that smaller wear was found in the ridge with the higher hardness, i.e. the one with the weld deposit.

4.2 Numerical model

The shape of the die was designed using DEFORM v11.1 in order to provide an optimum effect on the tool during the test. After the technological test was completed, the resulting shape was used for solving an inverse problem aimed at identifying the correct settings of the wear model. The geometry used for this purpose is shown in Fig. 10.

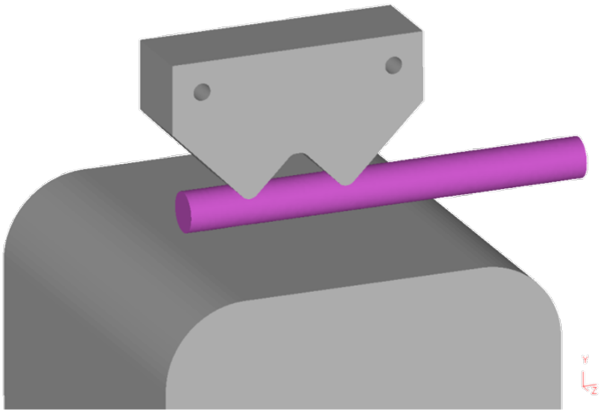

Figure 10. Numerical model of the technological test

The settings of the calculation were defined so as to obtain as accurate test description as possible, i.e. to correctly replicate all process parameters.

The tool wear calculation requires the finite element mesh to be created also for the body which is defined as a rigid body. As this forming process involves abrasive wear, the wear evaluation should preferably be carried out using the Archard model.

The wear calculation equation (1) uses input parameters which include the sliding velocity, the contact temperature, contact pressure and material hardness, i.e. either the secondary outcomes of the numerical calculation or values entered at the start of the calculation. Hardnesses for the ridges were defined according to their measured values. The tool steel ridge had a hardness of 55 HRC and that with the weld deposit was assigned 62 HRC.

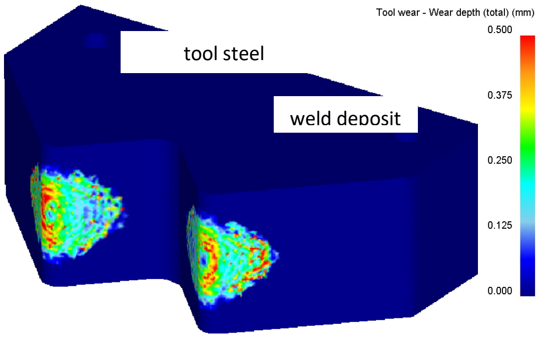

Figure 11. Wear prediction on the basis of FEM calculation

Fig. 11 presents the basic outcome of the numerical simulation: the total wear amount. One can also view the wear rate and the affected volume.

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The resulting wear distribution is in agreement with the real-world distribution found after the experiment. The only differences are related to the wear amount. The wear patterns in both ridges are in a relatively good agreement with the experimental findings.

5 CONCLUSIONS

Wear prediction methods are very important for practical tasks. When used correctly, they can deliver substantial cost savings in terms of field testing of a new technology.

At our company COMTES FHT, we have introduced several methods to determine the resistance of a material to service wear. Besides the standard tests, we have successfully trialled a technological test which was in-house-designed for calibrating numerical methods of wear prediction.

A die with two ridges can be used for not only refining numerical models of wear but also for testing new weld deposits or coatings.

Numerical calculations must be viewed as qualitative ones, i.e. as methods of predicting wear locations rather than the exact amount of wear. The main reason is that the amount of wear depends on the number of repetitions.

ACKNOWLEDGMENTS

This paper is a result of the project entitled Development of West-Bohemian Centre of Materials and Metallurgy No.: LO1412, which is funded by the Ministry of Education of the Czech Republic.

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