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Letters

Galling growth analysis in metal forming

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ABSTRACT

In this study, the applicability of adhesion calculations by an adhesion growth model, proposed by the authors, is investigated. The adhesion calculation results obtained by the adhesion growth model are compared with experimental results obtained under different sliding distance and contact surface temperature conditions. It is shown that the adhesion growth model can simulate the initiation and early stage behavior of galling.

1. Introduction

Dry metal forming processes have been paid considerable attention to due to the increasingly strict regulations that are aimed at reducing hazards from lubricants. However, when dry processes are performed, galling occurs. Moreover, galling leads to an increase in surface defects on the workpiece. The problems of galling have not been satisfactorily solved. The main reasons that galling behavior has not been sufficiently clarified are: (1) Galling phenomena are extremely complex because they are affected by many factors; and (2) Carrying out experimental studies to clarify the influence of these factors is a time- and cost-consuming process although many types of laboratory tribometers have been developed [1–3]. Thus, the influences of the above-stated factors have not been well quantified.

Basically, galling is caused by adhesion between the tool and the workpiece. From this perspective, the authors have constructed an adhesion growth model. The model calculates the growth of the adhesion area by considering the effects of the previously stated influential factors. In addition, the adhesion condition at each position can be quantified. The model has been verified by using experimental results obtained through a series of bifurcating extrusion type friction tests [4].

In this study, the adhesion calculation results obtained by the adhesion growth model are compared to experimental results obtained under various relative sliding distance and temperature conditions. By using this comparative analysis, the feasibility and the range of applicability of the model are investigated as a fundamental basis for proposing a design methodology for dry forming processes in which the occurrence of galling is minimized.

2. Adhesion growth model for metal forming

The adhesion growth model, which is proposed, calculates adhesion occurrence and its two-dimensional growth on the contact surface between the workpiece material and the die in metal forming processes. This model accounts for the following phenomena:

(1) When the temperature and combination of tool and workpiece materials are constant, the adhesion behavior can be determined by the magnitude of the relative sliding distance, pressure between the tool and workpiece, and the surface expansion ratio.
(2) When the criterion for ductile fracture is not satisfied around the surface under a high contact pressure condition, the adhesion area growth rate is small.
(3) Adhesion growth rates are proportional to exp(-1/T), where T: Temperature.
(4) Adhesion area growth rate increases with increasing contact pressure and is affected by the area ratio of the non-adhesion parts.

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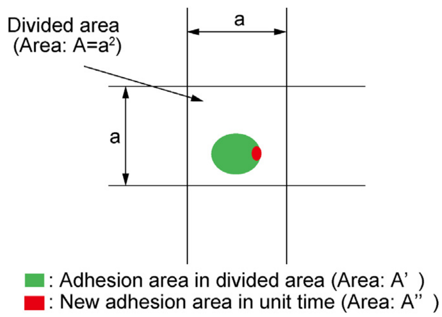

Fig. 1. Surface division when the influential factors change as a function of position and the definitions of each area.

The developed adhesion growth model is given by the following equations [4]:

$$ds = f(P,\eta)(1-s)K\exp(-\alpha/T)dL$$

$$f(P,\eta) = \begin{cases} 0\left(\frac{P}{\sigma_Y} > 1\right) \\ \frac{P}{\sigma_Y}\frac{\eta-1}{\eta}\left(\frac{P}{\sigma_Y} \leqslant 1\right) \end{cases}$$

where s designates the adhesion area rate, ds the increase of the adhesion area rate, η the surface expansion ratio (=(Area including the area expanded by pressure)/(Initial are)), P pressure,dL the increased amount of relative sliding, K and α constants determined by the combination of die and workpiece materials, and σ_Y the yield stress of the workpiece material.

In actual forming processes, the influential factors are both position- and time-dependent. In this case, ds at each position can be calculated by dividing the tool surface into grids as shown in Fig. 1. In this figure, s is defined by A'/A and ds is defined by A''/A. The calculations are performed by the following procedure:

Step 1: Selection of material constants (K, α, σ_Y);
Step 2: Evaluation of change histories of factors (P, η, dL) at each evaluation position;
Step 3: Calculation of $ds(= A''/A)$at each time step. Adhesion area rate $s = A'/A$ is calculated by integrating ds.

By this procedure, the adhesion area rate, s, can be obtained respectively in each divided area shown in Fig. 1. Here, in Step 2, the evaluation position is located at the center of each surface element when the finite element analysis is used for calculating the change histories of the influential factors (P, η, dL). When the change histories of the influential factors are obtained by experiment, the evaluation position coincides with the measurement points for the factors. For an adhesion area rate of s = 0.5, for example, adhesion occurs on half of the divided area.

3. Adhesion states in perpendicular cross-cylinder friction tests

3.1. Experiments details

Results of perpendicular cross-cylinder friction tests, reported by Jerina et al. [5], are compared with the calculated results by the above adhesion growth model. The materials used in this test are AISI H13 hot-worked steel (denoted as H13) and aluminum alloy EN AW-6060 (denoted as AW-6060). The H13 and AW-6060 samples were formed as cylinders, 10 mm in diameter and 100 mm in length. The surface roughness values of H13 and AW-6060 samples were $R_a = 0.036 \pm 0.006\mu m$and $R_a = 0.330 \pm 0.049\mu m$respectively. All the tests were performed

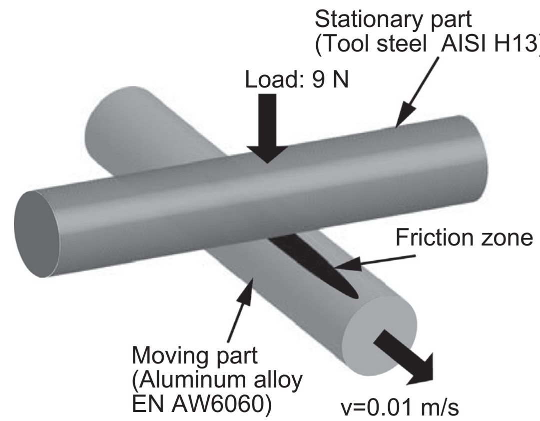

Fig. 2. Device configuration for the perpendicular cross-cylinder friction test [5].

in a perpendicular cross-cylinder configuration in single-pass sliding with a constant load of 9 N and a speed of 0.01 m/s as shown in Fig. 2. The results of the test which were performed for two sliding distances (2 mm, 68 mm) and two test temperatures (20°C, 200°C) are compared with the calculated results.

3.2. Finite element analysis conditions

For obtaining the change histories of the factors (P, η, dL), elasto-plastic finite element analysis was used. The analysis setup including the geometry of the model is shown in Fig. 3. The model used for analysis is a 1/2 model divided by the plane of symmetry (x-z plane in Fig. 3). In addition, one half of the cylinders, which includes the contact area, is modeled. The upper H13 cylinder is modeled only around the contact area (cylinder length is 5 mm in the 1/2 model). The H13 tool steel is assumed to be an elastic perfectly plastic body (Young's modulus is 200 GPa, Poisson's ratio is 0.3, and Yield stress is 1650 MPa) at all temperatures. When the temperature is 20 °C, AW-6060 is assumed to be an elastic perfectly plastic body having the following properties: Young's modulus is 70 GPa, Poisson's ratio is 0.3, and Yield stress is 270 MPa following properties. At a temperature of 200 °C, AW-6060 was assumed to have the following properties: Young's modulus is 60 GPa, Poisson's ratio is 0.3, and Yield stress is 90 MPa. The step size was adjusted in the solver (ABAQUS 6.14 Standard) for convergence. The step size varied from 0.00009 to 0.040536 sec. Under

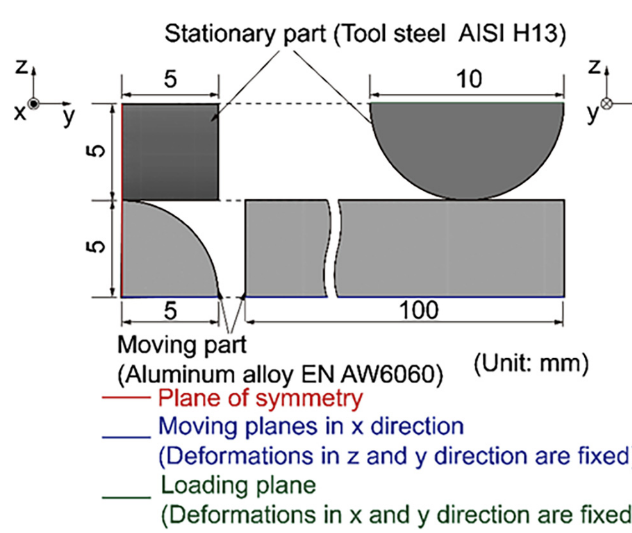

Fig. 3. Analysis model of the perpendicular cross-cylinder friction test.