Tool life prediction under multi-cycle loading conditions: A feasibility study

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Abstract. In the present research, the friction and wear behaviour of a hard coating were studied by using ball-on-disc tests to simulate the wear process of the coated tools for sheet metal forming process. The evolution of the friction coefficient followed a typical dual-plateau pattern, i.e. at the initial stage of sliding, the friction coefficient was relatively low, followed by a sharp increase due to the breakdown of the coatings after a certain number of cyclic dynamic loadings. This phenomenon was caused by the interactive response between the friction and wear from a coating tribo-system, which has not been addressed so far by metal forming researchers, and constant friction coefficient values are normally used in the FE simulations to represent the complex tribological nature at the contact interfaces. Meanwhile, most of the current FE simulations are single cycle, whereas most sheet metal forming operations are conducted as multi-cycle. Therefore, a novel friction/wear interactive friction model was developed to, simultaneously, characterise the evolutions of friction coefficient and the remaining thickness of the coating layer, to enable the wear life of coated tooling to be predicted. The friction model was then implemented into the FE simulation of a sheet metal forming process for feasibility study.

1. Introduction

In the metal forming industry, finite element (FE) simulations are widely used for process analysis and parameter optimisations. As the current FE simulations are mostly performed in single cycles only, this differs from the cycles experienced by industrial metal forming tools, which are normally operated for a large number of cycles. After a certain number of cyclic loadings, the tools can be damaged due to wear. It is of vital importance for engineers to understand the tribological behaviour in metal forming processes to enable tooling wear life prediction after cyclic loadings. Moreover, tools are often coated with hard coatings for the purpose of reducing friction, increasing hardness, wear and oxidation resistance [1]. In the past years, the tribological behaviour of coated surface contacts are characterised at different conditions. Cao et al. investigated the friction and wear behaviour of Cu/Cu-MoS2 self-lubricating coating applied on high speed steel, in which they found that the coated high speed steel

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Table 1. Coating process parameters.

Working pressure (Pa)	0.6
Cathode arc power (kW)	2
Magnetron sputtering power (kW)	4
Substrate bias (V)	-160
Nitrogen gas flow rate (sccm)	500
Deposition temperature (°)	350
Deposition time (min)	75

had better tribological properties [2]. Kim et al. performed ball-on-disk tests to examine the effects of sliding velocity and temperature on friction and wear of a multi-layered DLC coating, and found that the temperature rise led to a decrease in wear rates but an increase in friction coefficient, while the increased sliding velocity could reduce the wear rate and friction coefficient [3]. Hol et al. developed a physical based friction model which characterised the friction with surface topography, contact pressure and plastic strain [4, 5]. Wilson et al. presented a realistic friction model for sheet metal forming [6–9]. Ersoy-Nurnberg et al. simulated wear behaviours in sheet metal forming process by using an energy approach, in which Archard's wear model was modified to introduce variable wear coefficient [10]. Instead of being a constant value, the wear coefficient obtained by the energy approach was described in terms of the accumulated wear work [11, 12].

It is of great importance to carry out FE simulations for multi-cycle loading to predict the tool life for metal forming processes. Karupannasay et al. used a rotational friction tester to simulate the loading and reloading of the workpiece in a deep drawing process [13]. Pan et al. investigated a multi-cycle micro-forming process in terms of temperature changes in the die after cycles of loading, in which the heat transfer between the die and workpiece was given as a function of time [14]. Moreover, Krolczyk et al. have evaluated the life of coated carbide cutting tools [15], and Fujimoto et al. tested the endurance of a DLC coated die in micro-sheet metal forming [16].

The previous friction/wear tests and models reviewed have shown the wear and change of friction coefficient with both internal and external variables such as contact pressure and sliding speed etc. However, these variables could have interactive effects on the friction coefficient. Furthermore, studies on the evolution of friction and coating thickness for coated tools under cyclic loadings are insufficient. Therefore, in this paper, the friction coefficient and wear mechanism of a hard coating is modelled by using a novel friction/wear interactive friction model developed in [17] to characterise the evolution of friction and predict the coated tool life.

2. Experimental details

2.1 Sample preparation

The bearing steel GCr15 substrates were coated with TiN by mid-frequency magnetron sputtering and cathode arc. The experimental parameters used in the magnetron sputtering are given in Table 1 [17]:

In order to test the tribological properties of the TiN coated samples, a WC-6%Co ball with a diameter of 6 mm was used as a counterpart against the samples. The ball had a micro-hardness of 1780HV, abrasion strength of 1380N/cm and elastic modulus of 71GPa.

2.2 Ball-on-disc tests

A UMT-2 ball-on-disc tribometer was used to determine the evolution of friction coefficient, wear rate and wear volume, with a sliding speed of 5 mm/s. The cross-section of the sample was examined by SEM-JEM2010 scanning electron microscope to determine the thickness of the coating. The WS-2004 micro-scratch tester was used to examine the adherent strength. The micro-hardness and

nano-hardness of the samples were tested on a Wolpert Wilson Instruments Tukon 2500 hardness tester. The NewView[TM] 7100 white-light interferometric surface profiler was used to obtain the three dimensional surface profile before and after the test [17]. These physical and mechanical properties of the TiN coating were used in the interactive friction model developed in the present research.

3. The interactive friction/wear model

The friction and wear are two interactive responses of a coating tribo-system. The overall friction coefficient μ between the ball and the coating stems from the initial friction μ_α, and ploughing friction of hard wear particles μ_{Pc} (Eq. (1)) [17]. The dual-plateau feature of the ploughing friction μ_{Pc} is represented by Eq. (2), by linking the ploughing friction (μ_{Ps}) between the ball and substrate with the instantaneous coating thickness (h). This ensures that once the remaining coating thickness is zero, $\mu_{Pc} = \mu_{Ps}$. The model parameters λ_1 and λ_2 provide the flexibility and, in the meanwhile, represent the physical meaning of the wear process. λ_1 represents the effect of the entrapped large-size wear particles. At the initial stage of wear, the wear particles are loose-powder like and do not contribute to the ploughing friction. As the wear process proceeds, the coating starts to break down and more large-size wear particles are generated and they gather into large-size wear debris. Once the size of the hard wear debris is sufficient to be entrapped between the surface asperities, the effect of the ploughing friction due to the entrapment of the wear particles is initiated. The intensity of the ploughing friction effect is characterised by the model parameter λ_2, which is characterised by the slope of the COF. This friction model uses time based integration algorithm to capture the evolution of the remaining coating thickness, which is updated within each calculation loop by using Eq. (3). The benefits become pronounced when the accumulated wear effect under varying contact conditions is modelled. The classic Archard law (Eq. (4)) is modified and adopted in the present model to estimate the wear of the coating. The concept of the combined hardness (Eq. (5)) is employed to estimate the evolution of the coating hardness considering the thinning effect of the coating, in the meanwhile, the softening of the coating due to thinning is contributing to the wear rate increase (Eq. (4)). The ploughing friction, as a response to the coating thickness reduction (large wear particles entrapment), would increase correspondingly. As such, the interactive responses between friction and wear are realised in this friction model. Further details of this friction model can be found in [17].

$$\mu = \mu_\alpha + \mu_{p_c} \tag{1}$$

$$\mu_{p_c} = \mu_{p_s} exp\left[-\left(\lambda_1 h\right)^{\lambda_2}\right] \tag{2}$$

$$h = h_0 - \dot{h}dt \tag{3}$$

$$\dot{h} = \frac{kpv}{H_c} \tag{4}$$

$$H_c = H_s \left(\frac{\alpha^2 + h\beta^2}{\alpha + h\beta^2}\right) \tag{5}$$

$$\lambda_1 = k_{\lambda_1} P^{N_{\lambda_1}} \tag{6}$$
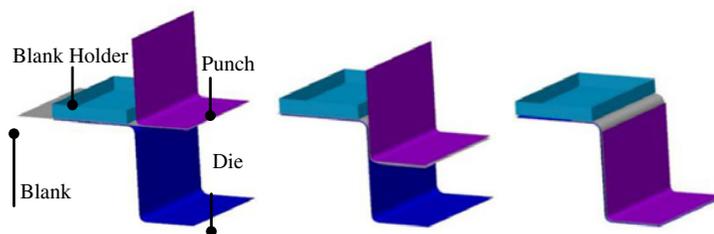
$$K = k_K P^{N_K}. \tag{7}$$

Figure 1. Schematic diagram of U-shape bending simulation.

Table 2. Geometry of the workpiece and tooling for the U-shape bending simulation.

	Blank	Blankholder	Die	Punch
Length/mm	120	80	95	5
Width/mm	80	52.35	80	80
Thickness/mm	1.5	-	-	-
Mesh size/mm^2	1.6	-	-	-
Height/mm	-	10	-	63.35
Fillet radius/mm	-	-	5	5

Table 3. Material constants for the friction model.

λ_2	μ_{P_s}	α	k_{λ_1}	k_K	μ_a	N_{λ_1}	N_k
2	0.311	6	4.58E17	7.27E-23	0.17	-3.84	4.095

The friction model parameters include load independent parameters, μ_{Ps}, and λ_2, hardness ratio between coating and substrate, α, and the coefficient of thickness, β. The model constants are k_{λ_1}, k_K, N_{λ_1} and N_K, which relate to the evolution of friction [17–21].

4. FE simulation details and implementation of the friction model

The friction model is implemented into PAM-STAMP for the simulation of U-shape bending (Fig. 1), in which the change of friction distribution and coating thickness after different numbers of cycles can be estimated. This cold stamping process is simulated as a symmetric model with a stamping speed of 75 mm/s. The geometry and other parameters used in the simulation are given in Table 2.

5. Results and discussion

5.1 Friction modelling results

The friction model constants of the hard coating used in the interactive friction model are determined from experimental results by using a numerical integration code, which is given on Table 3.

Once the model constants and parameters are determined, the evolution of friction coefficient and the breakdown of the hard coating can be predicted. As shown in Fig. 2, the interactive friction modelling results generally have good agreement with the experimental data under three different loads. For the contact between TiN coating and the WC-6% ball, the predicted friction coefficient curves start with a relatively low value of about 0.17, after a gradual increase of friction due to ploughing friction induced by wear debris, the coating starts to break down and the friction coefficients reach approx. 0.51. Meanwhile, the coating breaks down quicker as the pressure increases. According to Archard's wear law, the coating would be worn faster under higher normal loads [11]. In addition, since higher
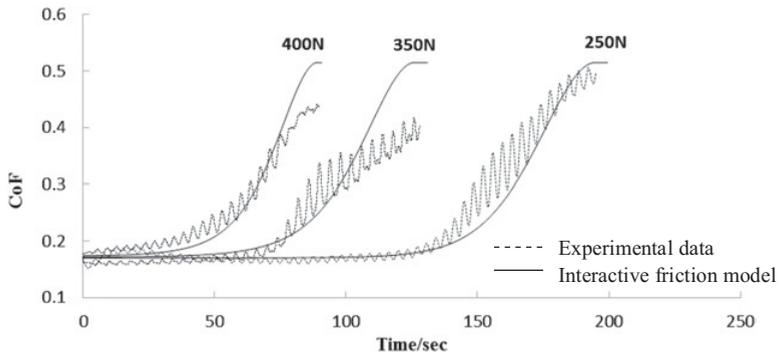
Figure 2. Evolution of friction coefficient by experimental data and friction model under different loads.
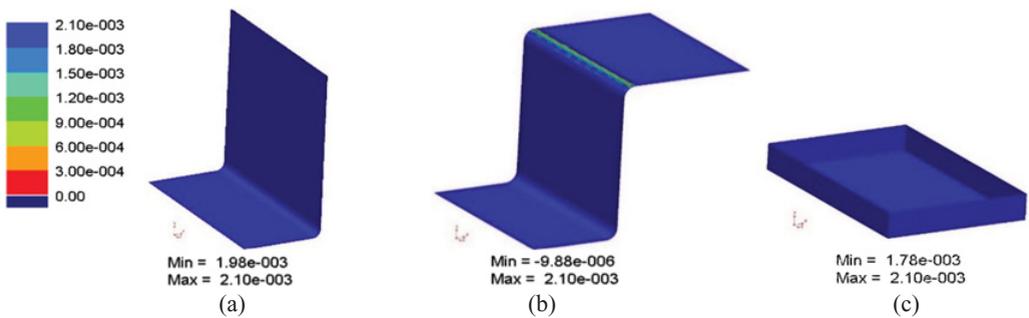

Figure 3. The remaining coating thickness distribution in the a) Punch b) Die and c) top blankholder, after 2000 times of forming cycles.

load is applied, the generation of the wear debris would be faster, owing to the higher wear rate, which consequently reduces the duration of the low friction region.

5.2 Tool life prediction: A feasibility study

Most of the FE simulations conducted for the sheet metal forming operations are single cycled with a constant friction coefficient/factor assigned as the boundary condition, which has almost ignored the evolutions of the interface conditions due to the multi-cycle loadings and probably over-simplified the complex tribological nature at the workpiece/tooling interface. The results shown in Fig. 2 clearly indicate that the friction coefficient evolved as an interactive response to wear. Therefore, the use of a constant friction coefficient, taking the average value over the entire life time of the coating or lubricant, could lead to considerable deviations from the actual contact conditions at the tooling/workpiece. The implementation of this interactive friction model has enabled the complex evolutions in friction coefficient and wear during the metal forming processes to be represented, which has enabled designers and engineers to define the frictional boundary conditions more sensibly. Moreover, the interactive friction model has enabled the estimation of the breakdown of the hard coatings, so that the life of the coated tools can be estimated. In the present work, the interactive friction model is implemented into the U-shape bending simulation, as a feasibility study. By using a stand-alone code developed in the authors' group, the evolutions of friction distribution and coating thickness of the tools after 500, 1500 and 2000 forming cycles can be obtained, without running the FE simulation of the forming processes for so many loading cycles, which saves significant computational efforts. Figure 3 shows the remaining coating
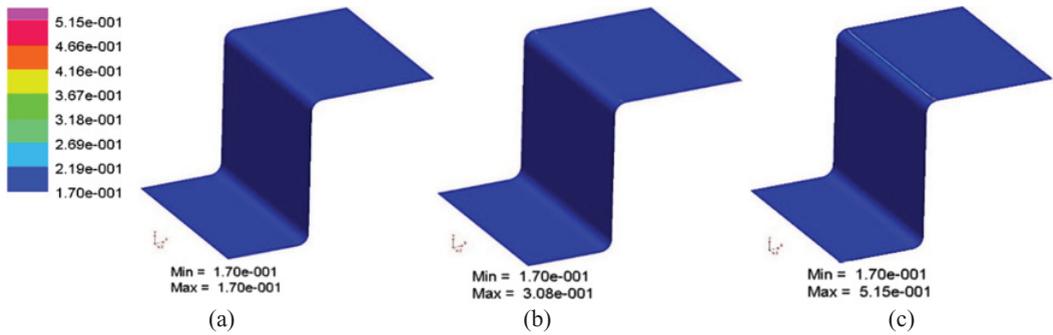
Figure 4. Friction coefficient distribution after a) 500 cycles b) 1500 cycles c) 2000 cycles of forming operations.
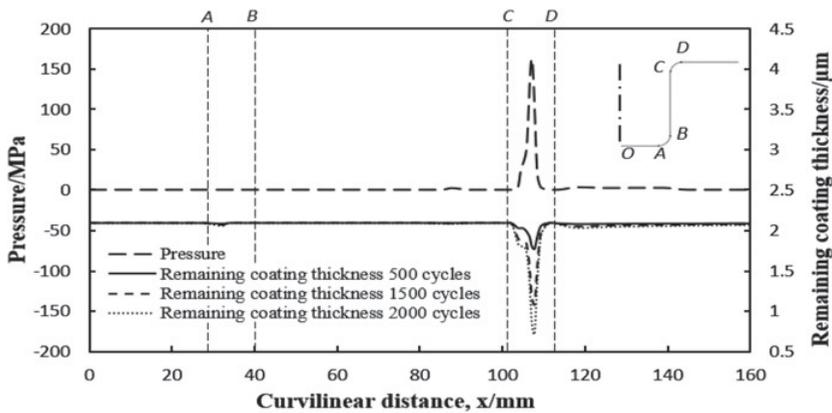

Figure 5. Prediction of contact pressure and remaining coating thickness along the curvilinear distance of the die.

thickness after 2000 forming cycles, in which the remaining coating thickness of the die, particularly the in the die entrance region, is much lower than the punch and blankholder, because this region of the die undergoes severe sliding wear caused by long accumulate sliding distance and high contact pressure. In the meanwhile, the friction coefficient increases correspondingly due to the decreasing coating thickness. As shown in Fig. 4, the friction coefficient in the main contact region increased to 0.308 and 0.515 after 1500 and 2000 forming cycles, respectively, while the friction coefficient of the die remained at 0.17 after 500 cycles suggesting that the coating started to breakdown after 1500 cycles of loading in the die entrance region, whilst both punch and blank holders are safe.

Figure 5 shows the pressure and remaining coating thickness distribution along the curvilinear distance of the die after 500, 1500 and 2000 forming cycles. Since the region CD represents the die entrance region during the U-shape bending process, the pressure in this region was much higher than the other region of the die. Consequently, the wear of coating mainly occurred in this area. The lowest remaining coating thicknesses after 500, 1500 and 2000 cycles were 1.773, 1.087 and 0.725 μm, respectively, while the initial coating thickness was 2.1 μm.

6. Conclusion

In the present research, the sliding wear tests of a hard coating have been conducted. It was found that friction and wear, as two interactive responses from one coating tribo-system, influence each other.

Therefore, a friction/wear interactive friction model has been developed which enables the prediction of the evolution of friction coefficient and the breakdown of the coating. The implementation of the interactive friction model into FE simulation has realised the tool life prediction for a sheet metal forming process.

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