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Wear Behavior of MoS_2 Lubricant Layers during Sheet Metal Forming

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Abstract

The increased use of high and ultra-high strength steel and materials with a high adhesion tendency leads to higher demands regarding the wear resistance of forming tools. A promising approach addressing both challenges is to apply MoS_2 dry film lubricant coating systems to the tool surface. These coatings reduce friction and the use of drawing oils and can also be used as an abherent. Once these coatings are exhausted, they can be chemically removed and reapplied. However, the tool life of the coatings cannot be predicted properly, due to their inhomogeneous wear behavior which depends on the forming parameters and differs locally. Moreover, there are carryover effects of MoS_2-particles to already ablated areas. Given the unpredictability of the wear of dry film lubricant coatings, it is not possible to plan the recoating cycles appropriately and thus, the potential of these coatings for commercial applications is limited.

In this research, the wear behavior of MoS_2-layers in deep drawing processes was investigated on a test stand with DP800+Z coil material which ensures realistic load conditions at the draw ring radius. Firstly, the wear pattern was determined and locally different contact pressures were recorded and assigned to respective wear areas. Due to bending effects of the sheet material, there are two major areas of wear on the draw ring radius. During wear tests, the wear-dependent coating thickness during wear initiation was determined by using 3D laser scanning microscopy and the friction force was evaluated.

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Keywords: Dry film lubricant coatings; wear initiation, wear behavior; 3D-Laserscan measurement

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1. Introduction

Molybdenum disulfide (MoS_2) belongs to the group of transition metal dichalcogenides and has a strongly anisotropic crystal structure. It consists of hexagonal layers of molybdenum, each molybdenum atom being surrounded by six sulfur atoms in a triangular array of prisms. Within one layer there are covalent bonds between the molybdenum and sulfur atoms, while the much weaker van-der-Waals bond prevails between the layers. This allows a sliding between these layers and leads to very low friction under certain conditions [1]. Moreover, there are carryover effects of MoS_2-particles to already ablated areas, which maintain the lubrication effect. In order to increase the wear resistance of MoS_2-layers, they are alloyed with titanium.

In most previous investigations of frictional coefficients and wear behavior of MoS_2-Ti-coatings a pin-on-disk-tribometer was used to determine the mechanical properties. Teer et al. [2] examined the influence of load on wear rate and friction. They showed that an increasing load leads to a lower coefficient of friction but higher wear on the surface. The same behavior was observed in various following experiments [1, 3, 4]. A suggested reason for this is the lacking supply of MoS_2 on the counter surface where due to the low contact pressure no adherent MoS_2-film can be formed [5]. The development of the frictional coefficient in case of high counts of repetitions with varied contact pressure was researched by Stoyanov [6]. No significant increase of friction was observed in over 1,200 circles. In former investigations even with 10,000 iterations the surface showed constant mechanical properties. Therefore, MoS_2-Ti-coatings are suitable for usage on forming tools which require a high amount of repetitions and increase lifetime significantly compared to uncoated tools [7].

The numerical formulation and experimental setup of contact conditions are essential to conduct research wear behavior in sheet metal forming processes. A deep drawing process can be segmented into three different phases of contact between the sheet metal and the draw ring radius during a deep drawing process. (1) The initial deformation describes the bending of the sheet over the punch and draw ring radius. (2) The intermediate stage describes the state in which the region of the sheet deformed at the start has not reached the wall of the tool yet. (3) Steady contact conditions define the final stage when the deformed material reached the side wall. [8]

Regarding tool wear, Pereira et al. suggest that the phases 2 and 3 are decisive for the contact pressure dependent wear of forming tools. The maximum pressure was identified during the intermediate stage. Two pressure maxima were determined at approximately 5° and 59° on the draw ring radius. However, the steady contact conditions occur during a much larger sliding distance between the sheet and the tool. The absolute pressure is lower and the second maxima shifts from 59° to 43°. [8]

The interrupted pressure patterns in combination with the pressure dependent wear behavior of MoS_2-layers leads to locally different life times of the coatings [9]. Furthermore, the pressure pattern heavily influences the carryover of MoS_2-particles. These two circumstances cannot be depicted by using the pin on disc method to conduct wear tests. The aim of this research is to enable numerical forecasts for the lifetime of MoS_2-Ti-coated forming tools. Therefore, a testing method has to be developed which ensures deep drawing specific load conditions to consider and measure the carryover effects of MoS_2-particles. Using such a testing method allows to conduct wear tests and to implement the results into a forming simulation.

2. Experimental setup

The experimental investigations on surface pressure and wear were conducted on a test stand with DP800+Z coil material to ensure realistic load conditions at the draw ring radius. The system is capable of representing the intermediate and the steady pressure conditions. The operation principle is depicted in Fig. 1. The sheet material is decoiled and transported with a gripper system consisting of two grippers. The first gripper is used for the feed and the second applies a restraining force which simulates the force generated by a blank holder during a common deep drawing process. The restraining force was set to 15.3 kN and the feed to 60 mm per stroke. The total test length sums up the test length of each stroke and will be used as the evaluation criteria. To record the pressure pattern on the specimen pressure indicating films were used. The indicating films were attached to the specimen. The specimen was coated with 4.5 µm TiN and 1.3 µm MoS_2-Ti. The TiN hard material layer prevents the actual specimen from being worn out. After the MoS_2-Ti-coating is locally removed, the golden color of the TiN is visible (Fig. 1).

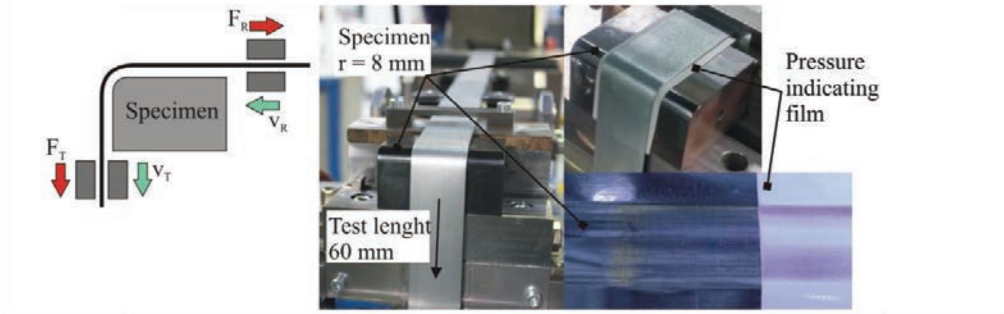

Fig. 1. Operation principle of the test stand and the pressure measurements

In order to analyze the layer ablation and surface quality of MoS_2-Ti-layer, profile analyzes were recorded by using a Keyence 3D laser scanning color microscope. This is a non-destructive method that is well suited for contactless measuring of the coating thickness of soft surfaces like lubricating layers.

After the wear test, the test specimen was cleaned with isopropanol in an ultrasonic bath in order to remove any wear residues as well as grease and oil. Then, the test specimen was fixed into the measuring appliance as shown in Fig. 2. In the aforesaid appliance, the test specimens can be adjusted on the basis of the wear marks. The main wear marks were approximately located at 10° and 60°. For every wear mark, three horizontal measuring surfaces were taken. The laser was always arranged in the perpendicular position to the surface of a test specimen. Three measuring lines (a, b, c) were set out on the surface, see Fig. 2b upper part. Every measuring line shows an own elevation profile which allows to draw conclusions about the layer ablation (Fig. 2b lower part).

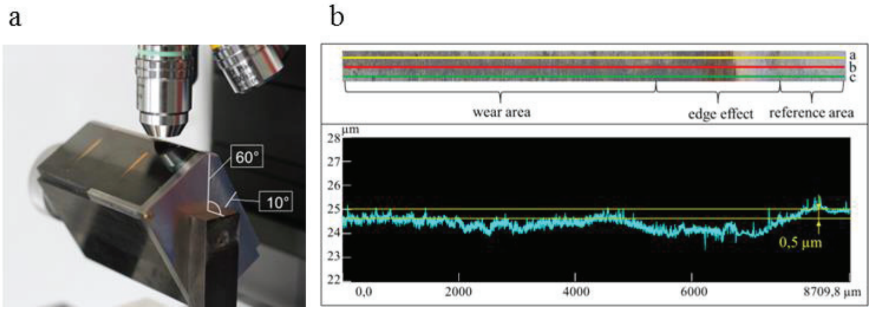

Fig. 2. (a) 3D-Laserscan microscopy, measuring setup, (b) Scanning surface with measuring lines, elevation profile

3. Numerical investigations

The numerical modelling of the experimental drawing investigation was carried out using the finite-element-system Abaqus CAE 6-13.1. Fig. 3 illustrates the model used for the numerical investigations. The coil was modelled using full-integrated shell elements with an edge length of 1 mm as a deformable body. Thus, the wear-specimen edge, which has a radius of 8 mm, is covered with enough number of elements which helps to avoid numerical failures, such as hourglassing or shear locking.

The elastic-plastic material behaviour of DP800 was determined using tensile tests carried out with the quench and deformation dilatometer DIL 805 A/D + T from TA Instruments. To obtain the flow stress at higher strains extrapolation approaches were tested, regarding the minimum deviation to the experimental data. The following Fig. 3 shows that neither the approaches of Swift [10] nor the approach of Hocket-Sherby [11] offered extrapolated data without great deviation to the experimental ones. Thus, a combined approach was created. This approach is based on the following equations:

Swift approach: $$k_f = a \cdot (b + \varphi^n) \quad (1)$$

Hocket-Sherby approach: $$k_f = c - (c - d) \cdot EXP(-m \cdot \varphi^q) \quad (2)$$

Combined approach: $$k_f = r \cdot Swift + (1 - r) \cdot Hocket - Sherby \quad (3)$$

with the constants a = 1230, b = 0.000393, n = 0.128, c = 1130, d = 460, m = 4.7, q = 0.574 and r = 0.194. For modeling the wear specimen as an elastic deformable body reduced integrated 3D-Solid hexahedral Elements were used. Thus, the distribution of the load as well as the contact normal stress can be calculated. The contact between the sheet metal and the specimen was modelled by the friction model of Coulomb, whereby the friction coefficient was numerically identified during the verifying process of the wear test model. The FE-Modell provides information about the local pressure. A subroutine was written to save the calculated maximum pressure for each element over the whole stroke. Using this subroutine a field variable is created to visualize the determined results as a contour plot.

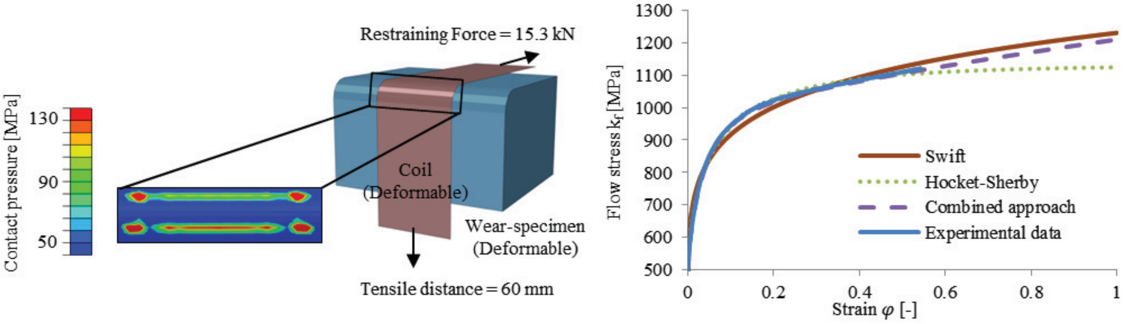

Fig. 3. The numerical model of the wear-specimen and the coil material for the wear tests

4. Results and Discussion

The experimental results show an interrupted pressure and wear pattern. Fig. 4a depicts the results of the indicating film measurements and the microscopic photograph of the specimen after 90 m of total test length. The load on both edges of the band is caused by bending of the material across the drawing direction. These edge effects have to be neglected because they are provoked by the testing method and do not resemble deep drawing conditions. The evaluation range lies between the two edges.

Fig. 4b shows the trend of contact pressure along the radius of the specimen. The pressure and wear pattern are characterized by two main contact areas. Contact area 1 is located at approximately 10° with a pressure maximum of 140 MPa. The second contact area occurs at about 63° with a pressure maximum of 145 MPa.

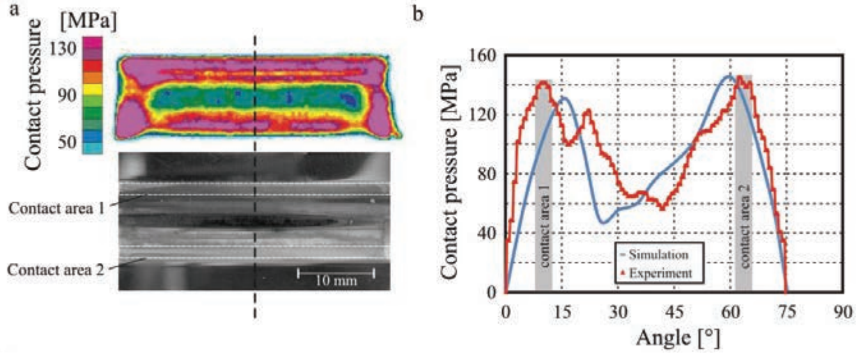

Fig. 4. (a) Comparison between the pressure and the wear pattern (90 m test length), (b) Contact pressure distribution

The numerical model of the specimen on the wear test was validated by comparing the numerical determined force displacement curve with the experimental one (Fig. 6b). During the verifying process of the model a numerical identification of the friction coefficient was carried out. Thus, a value of μ = 0.05 has been determined. The numerical investigations confirmed the experimental results concerning the development of two wear maximums at the inlet and outlet of the specimen's edge. Moreover, the comparison between the experimentally determined contact pressure and the calculated ones along the indentation path on the specimen shows a good agreement.

In order to ensure a transformability of the pressure and wear pattern to actual deep drawing processes, a validated [12] numerical model (Fig. 5) of a conventional deep drawing process was investigated. This investigation showed that the contact stress is concentrated at the edge of the lower die and especially at the inlet and the outlet of it. Moreover, the study confirmed high values of the contact stress, which reaches local maxima of 250 MPa. The contact zones on the sides of the rectangular die, which can be compared to the experimental setup, exhibit contact pressures of approximately 180 MPa.

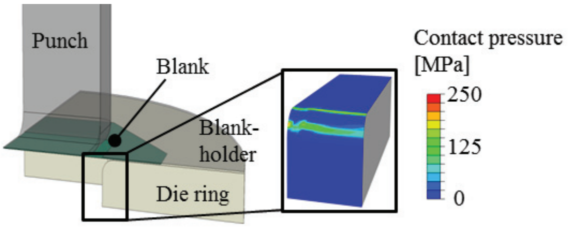

Fig. 5. FE-modelling of a conventional deep drawing process

To monitor the development of the friction force, firstly the trend of the restraining force and the resulting tension force were recorded during one stroke of 60 mm test length. The tension force consists of the applied restraining force and a reaction share caused by bending and friction. Secondly, the tension force was divided into the bending and friction share by using a rotating shaft (Fig. 6a) instead of the wear specimen. Fig. 6b depicts the trend of the friction, bending and restraining force. While the bending and the restraining force can be considered as constant during a series of wear tests the friction force is variable.

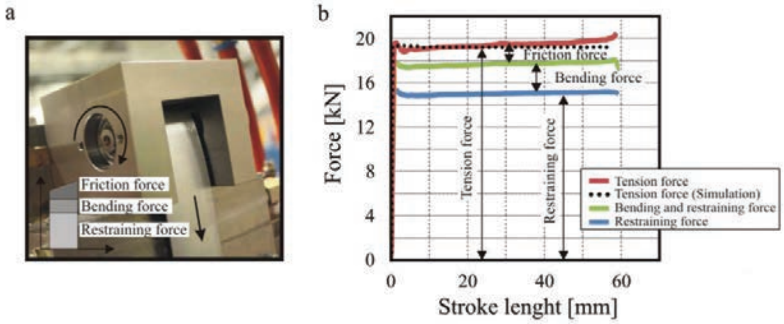

Fig. 6. (a) Rotating shaft to record the bending force, (b) Process forces during a test stroke of 60 mm

Fig. 7 illustrates the measured wear ablation of the test specimen during the wear initiation after 30, 60 and 90 m test length. The wear ablation can be seen at the second main wear mark around 63°. The layer ablation is not uniform, because the MoS_2-lubrication-layer is repeatedly dragged over the wear area and thus ensures a further lubrication. Therefore, an ablation was determined at first, however, after 60 m total test length a material application was already detected because of the entrainment of the MoS_2-layer. After 90 m, a new material ablation can be seen. After all displayed strokes, a continuous ablation in the upper part of the wear mark as well as a moving up lubrication layer in the middle and lower sections become visible.

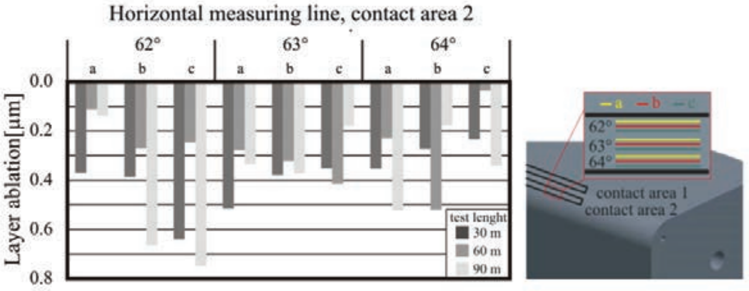

Fig. 7. Measurement results of the coating ablation during wear initiation

5. Conclusion

As pointed out in the literature and the experimental investigation, the wear behavior of MoS$_2$-Ti-coatings is very complex. In this paper a testing method for the complex behavior is presented which ensures realistic load conditions on the draw ring radius and measures carryover effects. Furthermore, it was possible to record the contact pressure and assign it to the respective wear areas. This is the decisive step to implement local life time data of the coating in FE based forming simulations and enable these simulations to forecast the coating life time for industrial application.

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