Tribology International 114 (2017) 418–428

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Using a standard pin-on-disc tribometer to analyse friction in a metal forming process

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ARTICLE INFO

Keywords:
Pin-on-disc tribometer
Friction analysis
Bulk metal forming

ABSTRACT

Tribological conditions in bulk metal forming processes are characterized by high contact pressures and large relative movements at high velocities between the tool and the workpiece. In addition, significant surface enlargements and elevated temperatures can occur. It is very challenging to reproduce such contact conditions on pin-on-disc tribometers.

In this study, a method for simulating the contact conditions of a metal forming process on a pin-on disc tribometer is presented. Special test samples have been designed in order to achieve high contact pressures and surface enlargements with a homogeneous distribution of these quantities within the contact zone. It is shown that the test method delivers reproducible results and enables the detection of small changes of the contact conditions. Furthermore, microstructural changes of the real contact surface can also be simulated, which was verified by SEM imaging.

1. Introduction

Tribological conditions in metal forming do not only affect the forming force and the wear rate of the tooling, but also the dimensional accuracy and the surface roughness of the formed parts. Thus, it is crucial that the lubricant system is properly adapted to the conditions of a particular forming process. Since the number of available lubricants is growing continuously along with new ecological demands, qualified selection and optimization methodologies have become increasingly important. Indeed, tests on the production line exactly represent the real forming conditions, but they are cost extensive because the manufacturing process needs to be interrupted. Moreover, friction influencing parameters such as contact pressure, surface enlargement or relative sliding velocity are difficult to analyse since they are changing temporally and locally within the contact zone. Hence, tribological test rigs are indispensable to investigate and further optimize lubricant systems, not only in metal forming.

While the strip test is a generally accepted test method for the assessment of friction and wear in sheet metal forming, no such test exists in the field of bulk metal forming [1]. In recent years, several test methods have been proposed, which are focused on specific bulk metal forming processes. An excellent overview and comparison of the most common test methods is given in [2,3]. One of the oldest methods to investigate friction in bulk metal forming is the ring compression test, originated by Kunogi [4] and later improved by Male and Cockroft [5]. The method is based on the change of the inner diameter of a flat ring due to deformation. In order to simulate the frictional conditions of an extrusion process, Lahoti and Altan [6] proposed the spike test. Here, a cylindrical specimen is pushed into a conical converging groove. As reported by Isogawa et al. [7], the height of the spike strongly depends on the coefficient of friction. Zhang et al. [8] developed a similar test method in which a cylindrical specimen is compressed between a flat punch and a V-grooved die. In this so called T-shape compression test, the height of the extruded part is used as a measure of friction. Another well-established test method, often used to simulate frictional conditions in cold forging, is the double cup extrusion test. It was introduced by Buschhausen et al. [9] on the basis of the experimental work of Geiger [10]. Here, the ratio of the height of two cups, which are built during forming, acts as a sensitive measure of friction. Similar test methods have also been proposed by other authors, especially to study the frictional conditions in extrusion processes [11,12].

With the exception of the strip test, all test methods mentioned so far are based on the formation or change of a geometrical feature during deformation. Due to this indirect approach, calibration curves,

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http://dx.doi.org/10.1016/j.triboint.2017.04.052
Received 2 March 2017; Received in revised form 28 April 2017; Accepted 30 April 2017

either determined analytically or by means of the finite element method (FEM), are needed to evaluate the coefficient of friction. A direct measure of the coefficient of friction was introduced by Bay et al. [13]. The method, originally used to study the friction in forging, is based on the torque measurement of a rotating billet. In order to study the friction in drawing processes, Rigaut et al. [14] developed the upsetting sliding test. Here, an inclined front surface indenter is pressed and moved over the surface of a cylindrical specimen. The coefficient of friction is calculated from the ratio of the measured normal and tangential force. The upsetting sliding test has been further improved by Dubois et al. [15,16] in order to enlarge the range of applications of this test method.

A drawback of nearly all test methods mentioned so far is that at least one of the friction influencing parameters, such as contact pressure, surface enlargement or sliding velocity, is not constant within the contact zone. This often hinders a systematic analysis of the parameters of interest. Furthermore, the described testing methods are focused on specific metal forming processes. This in fact provides a high level of comparability, but leads to a loss of flexibility at the same time. To overcome these problems, Hemyari [17] proposed a testing method called sliding compression test. A detailed description of this test is given in Groche et al. [18]. Another test rig, which enables a direct and flexible analysis of friction, is the pin-on-disc test. However, on a pin-on-disk tribometer the conditions of bulk metal forming processes, especially high contact pressures and surface enlargements, are hard to achieve by using standard test samples such as balls, cylinders, pins and discs.

The aim of this paper is to present a method for simulating the tribological conditions in a tube drawing process on a standard pin-on-disc tribometer. First, the contact conditions in tube drawing were analysed by means of FEM. In order to accurately reproduce the contact conditions on a pin-on-disc tribometer, special test samples were designed. The geometry of the test samples was optimized by means of FEM so that almost constant surface enlargements and contact pressures were obtained within the contact zone. In order to assess the sensitivity of the test method and the reproducibility of the obtained results, different contact parameter combinations, which are characteristic for tube drawing, were tested. By means of scanning electron microscopy (SEM), it was analysed whether the microstructural changes of the surface, which occur in the real forming process, can be simulated as well.

2. Analysis of the contact conditions in tube drawing by means of finite element method

Cold tube drawing is a manufacturing process where the cross-sectional area of a tube is reduced by drawing it through a conical converging die. This way, high quality tubes with an excellent dimensional accuracy as well as a low and homogeneous surface roughness are produced. In the case being considered, a tube with an initial outer diameter of 45 mm and a wall thickness of 5.8 mm is drawn through a conical converging die having a semi cone angle of around 10 degrees. After forming, the tube has an outer diameter of 33 mm and a wall thickness of 5.24 mm. The wall thickness and the inner diameter are calibrated with a cylindrical plug located in the middle of the die. The tubes consist of medium-carbon steel and the tools are made of cemented carbide. In order to reduce friction, the tubes are treated with zinc phosphate and stearate soap prior to forming.

The contact conditions in tube drawing were analysed by means of FEM with the commercial software MSC Marc/Mentat® (MSC Software Corporation, USA). A 2D axisymmetric thermo-mechanical simulation was performed since the die, the plug and the tube are aligned concentrically (Fig. 1).

During drawing, the tube temperature rises since nearly all of the forming and frictional energy is transformed into heat. However, after a short period of time a thermal equilibrium is established due to heat conduction to the die and the plug. Afterwards, the process can be treated as steady state with no significant variation of the contact conditions. Thus, only a short piece of the tube with a length of 200 mm was considered in the FE simulation. Linear order elements with four nodes and four integration points were used for the discretization of the geometry. The elements had a size of about 0.5 mm.

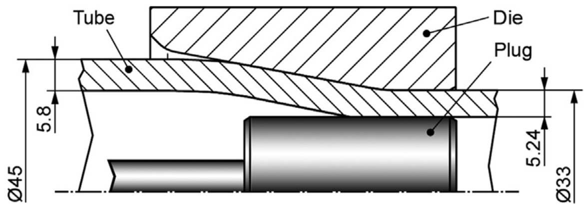

Fig. 1. Technical drawing including tube, die and plug in axisymmetric representation.

The material was modelled as isotropic elastic-plastic. The plastic flow of the material was described with a mathematical model based on the mixed hardening law according to Chaboche [19]. The model describes the flow stress in dependence on strain, strain rate and temperature. Furthermore, it also considers a possible Bauschinger effect [20]. This is achieved by a displacement of the yield locus, numerically represented by the backstress. The backstress tensor was described according to Ziegler [21], while its components were determined depending on the plastic strain according to the model of Armstrong and Frederick [22].

The contact between the tool and the workpiece was defined so that no penetration can occur and the heat transfer coefficient was modelled depending on the contact pressure according to Lechler [23]. In order to study the influence of friction on contact pressure, surface enlargement and temperature, the calculations were performed frictionless and with a Coulomb friction coefficient of μ=0.05 and 0.1, respectively. For the same reason, different forming velocities of up to 60 m/min were applied in the calculations.

In Fig. 2, the results from the FE calculations are presented. The contact pressure between the tube and the tooling is shown in Fig. 2a. The initial contact between the tube and the die occurs at a position of around 23 mm, while the first contact between the tube and the plug occurs at a position of around 43 mm. Since the tube does not run tangentially into the die and the plug, a high contact pressure of nearly 1000 MPa appears at the points of initial contact. However, apart from the points of initial contact, the contact pressure is significantly lower. A dependence on the coefficient of friction can be noticed, where higher friction values lead to a slight reduction of the contact pressure. On the other hand, forming velocity has no effect on the contact pressure.

Straining of the surface during forming leads to a change of its area. This change in area is commonly termed as surface enlargement. In tube drawing, the surface enlargement can be calculated as the sum of the logarithmic plastic strains in axial and tangential direction. As shown in Fig. 2b, the area of the surface is changed already prior to the point of initial contact. This is because the tube is bent into the die. Due to the bending, the area of the outer surface of the tube is initially enlarged, whereas the area of its inner surface is reduced. Subsequently, the area of both surfaces is reduced until the tube contacts the plug. Afterwards, the area of both surfaces is significantly enlarged. At the end, the surface enlargement is around 15% at the outer surface of the tube and around 9% at the inner surface of the tube. In the FE simulation, the surface enlargement depends neither on the coefficient of friction nor on the drawing velocity.

In contrast, the surface temperature strongly depends on the coefficient of friction and the drawing velocity, as shown in Fig. 2c. Thereby, higher coefficients of friction and drawing velocities lead to a higher surface temperature. The maximum temperature occurs at a position between 43 and 52 mm, where the tube is in contact with the plug. In this region, the temperature is increased by up to 200 °C,