Tribology International 82 (2015) 375–386

Contents lists available at ScienceDirect

Tribology International

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

Identification of lubrication regime on textured surfaces by multi-scale decomposition

C. Hubert [a,b,*], K.J. Kubiak [c], M. Bigerelle [a,b], A. Dubois [a,b], L. Dubar [a,b]

[a] Univ Lille Nord de France, F-59000 Lille, France
[b] UVHC, TEMPO EA 4542, F-59313 Valenciennes, France
[c] University of Liverpool, School of Engineering, Liverpool L69 3GH, United Kingdom

ARTICLE INFO

Article history:
Received 2 August 2013
Received in revised form
1 January 2014
Accepted 1 April 2014
Available online 2 July 2014

Keywords:
Roughness
Friction
Curvature radius
Fractal

ABSTRACT

This paper focuses on the analysis of surfaces resulting from thickness reduction of aluminium strips, provided with lubricant reservoirs, and deformed with different lubricant viscosities and drawing velocities, by a specific experimental drawing process. During reduction, the lubricant is pressurized and may escape from its initial cavities and supply the neighbouring ones. The nature of the lubrication regime is thus locally changed and may vary from boundary to hydrodynamic. The deformed surfaces are measured by means of a Vertical Scanning Interferometer then analysed in terms of arithmetic roughness and developed roughness profile length. Since these two parameters are found not accurate enough to identify regions where different lubrication phenomena occurred, a method based on roughness peaks and valleys curvature radii estimation, recently developed by some of the present authors, is applied.

The acquired surfaces are assumed as fractal surfaces and a multiscale decomposition of the peaks and valleys curvature radii of roughness profile is performed, for each experimental test. Then the analysis of the deformed surfaces is achieved and the effects of the different testing conditions on the curvature radii are highlighted. During this study, this method has been of great help to qualitatively define the different contacts nature, *i.e.* severe or not, and to link the different regions to a lubrication regime.

1. Introduction

Metal forming operations generally require mixed lubrication regime to reduce the friction at the tool/workpiece interface and to improve the visual aspect and roughness of the final surfaces [1]. The peculiarity of this lubrication regime lies in the fact that only the micro-cavities, inherent from surfaces roughness [2], are filled with lubricant during the contact, and thus the peaks of both surfaces are in dry contact. In plane strain processing, when plastic deformation occurs, the cavities filled with lubricant are pressurized and release the lubricant towards the drawing direction or in the opposite direction, according to the involved phenomena: Micro Plasto HydroStatic Lubrication (MPHSL, governed by the pressure gradient between the cavity and the contact pressure) or Micro Plasto HydroDynamic Lubrication (MPHDL, mainly governed by the relative speed between the tool and the worked surface), respectively. The result of this lubricant escape is a local change of lubrication regime that may become hydrodynamic rather than the initially expected, mixed lubrication regime.

The concept of Micro Plasto Hydrodynamic Lubrication (MPDHL) was first proposed by Mizuno and Okamoto [3] and later by Kudo et al. [2]. Azushima and Kudo [4] and Bech et al. [5] proved it in plane strain drawing of aluminium strips on which pyramidal indentations were manufactured and filled with lubricant. The lubricant dynamic behaviour was observed through a transparent glass die and recorded by means of a video camera. The aim of the latter study was to determine the drawing parameters, such as the lubricant viscosity, drawing speed, back tension or friction coefficient, that lead to MPHSL and/or MPHDL. This study also showed strong changes in the worked surface roughness where MPHSL and MPHDL occur, but has not been investigated further. More recently, Dubar et al. [6] carried out similar kind of experiments, with the same testing device as [5], but with triangular sectioned grooves as lubricant reservoirs, machined by means of Electro Discharge Machining (EDM). The aim of this technique was to avoid metal banks due to the indentation process, to avoid any lubricant escape perturbation due to these banks and to confer true plane strain properties to the analysis, including the lubricant escape. The drawing parameters

* Corresponding author at: UVHC, TEMPO EA 4542, F-59313 Valenciennes, France. Tel.: +33 3 27 51 14 54; fax: +33 3 27 51 13 17.
E-mail address: cedric.hubert@univ-valenciennes.fr (C. Hubert).

http://dx.doi.org/10.1016/j.triboint.2014.04.035
0301-679X/

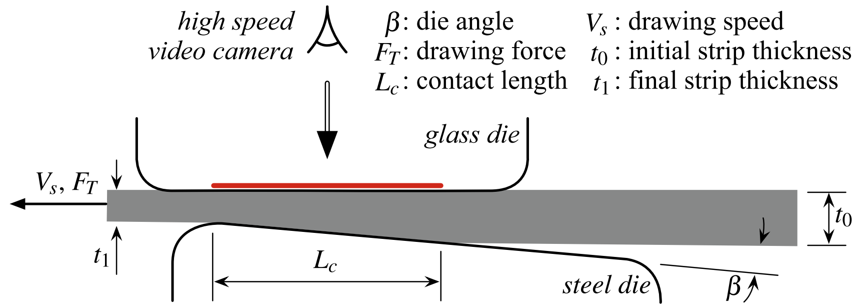

Fig. 1. Experimental testing device with its intrinsic parameters [14].

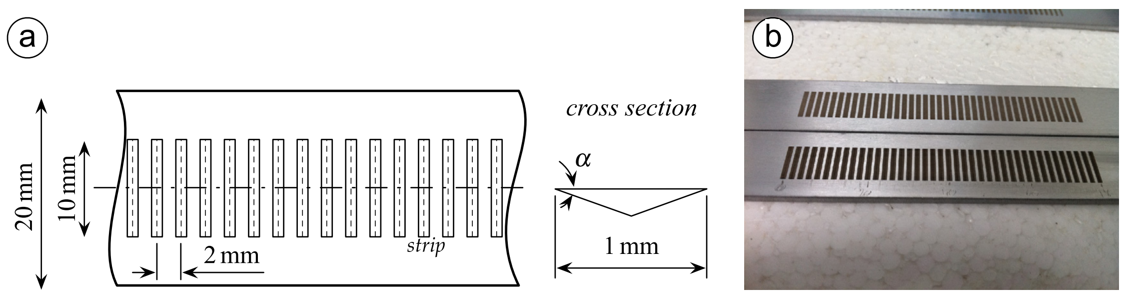

Fig. 2. Groove shaped pockets pattern (a) and picture (b) of two EDM processed strips.

investigated in this study were the drawing speed, the lubricant viscosity and the pockets angle to the edge, with goal to model numerically the lubricant reservoirs depth reduction due to plastic deformation and subsequent fluid escape during drawing, by means of a Fluid Structure Interaction model. Other studies focusing on related phenomena in drawing process like friction, lubrication, roughness etc. have been carried out [7–11]. In the present study, the experimental results produced by Dubar et al. [6] are used to analyse the effects of lubricant escape on the final roughness of the worked surfaces.

As classical tribological parameters such as the arithmetic roughness (R_a) or the developed profile length (R_{L0}) do not allow clear identification of regions where different phenomena occur [12], the method based on roughness peaks curvature estimation, which plays an important role in contact pressure, recently developed by Bigerelle et al. [12] is applied. This method considers the specimens surfaces as fractal surfaces and thus allows to perform a multiscale decomposition of this radius of curvature. Even if the calculation of the radius of curvature requires smooth surfaces, it is not always the case when dealing with fractal surfaces, as shown by Mandelbrot and Wallis [13]. Moreover, as all metric parameters relative to fractal curve depend on the measurement scale, it becomes difficult to give a physical sense of the local radius of curvature for fractal surfaces. And if in tribology contact fractal surfaces are often used to avoid sensitivity of the measurement scale, this approach is used here to identify the regions where different contact conditions occurred, especially a local change in lubrication regime due to either MPHSL or MPHDL.

The present paper is divided into three parts. Firstly, the experimental tests carried out are described: the testing device functioning is detailed as well as the specimens preparation and properties, and the testing conditions. Then the methodology for the acquisition of the worked specimens topographical information is explained. Secondly the methodology to perform the whole multiscale decomposition of the radius of curvature along a given topographical profile is described. Then, based on the prior multiscale decomposition, the analysis of the results is carried out to quantify the effects of the experimental process parameters (*i.e.* the lubricant viscosity, the drawing velocity and the pockets angle) on the radius of curvature measured on the final surfaces. Finally the link between this radius of curvature and the lubrication regime is presented, with comparison to regions outside of the pockets row and to initial profiles. The results are then discussed and proposals for future works are given.

2. Experimental tests and surfaces topography acquisition

2.1. Testing device and design of experiments

The experimental testing device used in this study has been developed by Bech et al. [5] for thickness reduction of aluminium strips. The strips are drawn by means of a hydraulic jack between two dies: the upper one is made of hardened glass so the lubricant behaviour can be observed during thickness reduction, and the lower die is made of steel with an inclined plane with angle $\beta = 3^{\circ}$ to apply the thickness reduction. The hardened glass is used as delivered in shape of circular disc of dimensions $\varnothing 50 \times 11$ mm, and the lower die is 80 mm long and 50 mm wide, with polished contacting surface to reduce friction. A high speed video camera is used to record the lubricant behaviour for subsequent analysis, *i.e.* identification of the occurrence of MPHSL and MPHDL, location of the onset and direction of escape or front wave speed. The testing device is illustrated in Fig. 1.

The provided strips dimensions are $l_0 \times L_0 \times t_0 = 450 \times 20 \times 2$ mm^3 and their material is a semi-hardened aluminium AISI 1050 H24. Macro lubricant pockets are manufactured by means of Electro Discharge Machining to reduce the local residual stresses and to avoid the formation of banks that would change the tribological contact properties and fluid escape, as observed in a prior study [15]. The shape of the lubricant pockets is a groove normal to the drawing direction with triangular cross section. They are 10 mm long and 1 mm wide, with an angle to the edge $\alpha = 5^{\circ}$ for the first set of specimens, and $\alpha = 10^{\circ}$ for the second one. The spacing between each cavity centre is 2 mm, so that the plateaus are 1 mm wide. The strips are obtained from cold rolling and their raw roughness is preserved all along the specimens preparation process. An illustration of the manufactured strips and an illustrative picture are given in Fig. 2.