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A combined numerical and experimental approach for determining the contact temperature in an industrial ironing operation

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ABSTRACT

Tribological conditions in forming operations depend on several parameters such as tool-workpiece interface pressure, surface expansion, sliding length, sliding speed, tool and workpiece materials and the roughness of the parts. Among indirect parameters, the most influential one is the tool-workpiece interface temperature, which directly influences the lubricant performance. Prior to testing new tribo-systems to determine their limits of lubrication, it is therefore important to find the interface temperature. However, measurement of the interface temperature in metal forming is difficult. The present work investigates the determination of the interface temperature in an industrial ironing operation, where severe process parameters lead to lubricant film breakdown and galling after several strokes. The methodology combines finite element simulations and experimental measurements. The overall procedure is based on a steady-state thermal analysis to determine the temperature distribution within the tool and a transient thermo-mechanical analysis of the ironing process when steady-state conditions are achieved. Results show that the proposed methodology applied to a single stroke can effectively and accurately predict the interface temperature in the test tool, thus avoiding the otherwise required thermo-mechanical FEM analyses of hundreds of strokes to reach steady-state. Furthermore, the influence of parameters, such as the predicted steady-state tool temperature, the friction coefficient and the heat transfer coefficient on the contact temperature, is analysed. It is concluded that the frictional heating is the primary cause for the peak temperature. By calibration of the friction coefficient and the heat transfer coefficient to ensure matching of the numerical results and the experimental measurements, a maximum tool-workpiece interface temperature of 158 °C was determined during the forward stroke and 150 °C during the backward stroke.

1. Introduction

Up to 95% of the mechanical energy involved in metal forming processes is transformed into heat. The generated heat partly stays in the deformed material, partly flows into the undeformed region, the tooling and the environment. The distribution and the level of the temperature in a forming process mainly depend on the initial temperature of each component, the heat generation through friction and plastic deformation, and the heat transfer between the parts and the lubricant and the parts and the environment (Farren and Taylor, 1925).

The prediction of the tool-workpiece interface temperature in a metal forming process is an important issue due to its effect on friction and lubrication. Increasing temperature implies lower viscosity of the lubricant, diminishing film thickness and the risk of film breakdown, metal-to-metal contact between tool and workpiece surface, pick-up and galling (van der Heide and Schipper, 2003; Olsson et al., 2004; Friis et al., 2008; Ceron et al., 2014). Increased temperature due to forming may on the other hand also facilitate the process in some cases. In solid film lubrication (e.g. in cold forging lubrication with conversion coating and soap), increasing temperature results in lower friction (Wibom et al., 1994; Bay et al., 2011). In boundary lubrication, the lubricant additives may be activated at a certain temperature level. By chemical or physical adsorption or by chemical reaction, a boundary layer of only one or a few molecules can prevent metal-metal contact to be formed (Schey, 1970).

Determination of the tool-workpiece interface temperature has been a subject of intense research. A way to measure the interface temperature experimentally is to establish a hot junction between the

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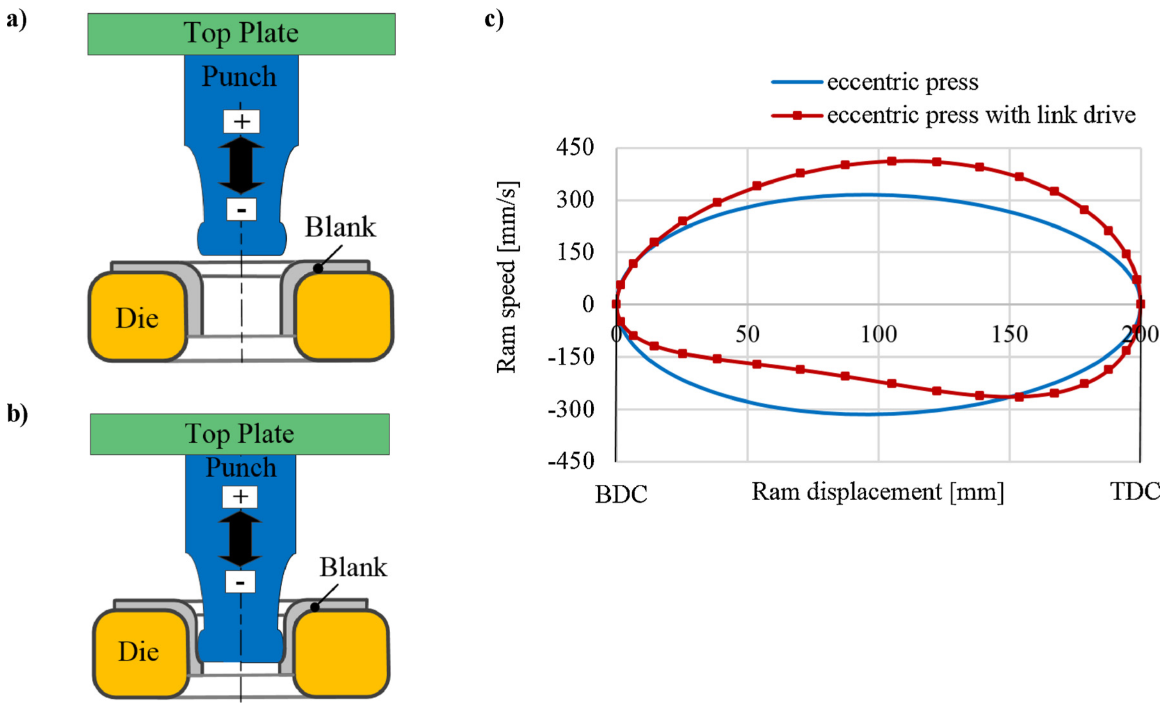

Fig. 1. a) Tool set-up for ironing, open tool, b) set-up during ironing, c) ram speed as a function of ram displacement. The direction of the velocity pattern is clockwise. BDC and TDC indicate the bottom and top dead centers.

thermocouple wires at the contact interface (Jimbo et al., 1998). Alternatively, the two conductor metals can be placed onto a surface if it has uniform temperature and is conductive (Henningsen et al., 1998). When the access to the contact is limited, the thermocouple wires can be welded into the tool, close to the surface contacting the workpiece material, while making sure that the drilled holes do not weaken the rigidity of the tool (Nielsen et al., 2011). This indirect measurement technique requires extrapolation by analytical or numerical solutions for an accurate estimation of tool-workpiece temperature.

Pereira and Rolfe (2014) have studied sheet stamping of high strength steel on a single-action, mechanical press in order to investigate the friction- and deformation-induced heating. They developed a thermo-mechanical, numerical model and validated their predictions against temperature measurements at a low speed. Then, the numerical model was used to replicate the production-type operation condition with 32 strokes per minute (spm). They found that the frictional heating was the primary cause for the peak temperature at the die surface. However, the developed model did only emulate single-stroke operations. Fallahiarezoodar et al. (2016) have investigated the temperature increase in the tool-workpiece interface in U-channel drawing and deep drawing for single as well as multiple strokes. They found that the maximum temperature rise in the tool-workpiece interface reached 120 °C in only nine strokes. It is vital to ensure that the process is in a steady-state condition before determining the interface temperature. Nielsen et al. (2011) predicted the tool-workpiece temperature for an industrial deep drawing and ironing operation of AISI 304 stainless steel, performed in a five-step progressive tool. They measured the tool temperature 2 mm from the contact surface in the final ironing operation during which the wall thickness was reduced by 25%. The developed thermo-mechanical model simulated 100 strokes. The numerically calculated temperature was then compared with the experimental measurements for validation of the model. They determined the maximum interface temperature to 110 °C in the production test at 100 spm using a PM tool steel, Vancron 40, as tool material and a chlorinated paraffin oil, Castrol PN226, as lubricant. Afterwards, they tested various tribo-systems in laboratory conditions using the previously found industrial interface temperature. However, they reported very long CPU time and convergence problems using DEFORM™ 2D. State of the art shows that determination of interface temperatures in industrial metal forming is performed either for a limited number of strokes without ensuring steady-state production conditions or by inefficient numerical modelling.

The present study reports on the determination of the contact temperature in a tribologically severe multistage deep drawing and ironing process applied by the Danish company Grundfos. The aim is to analyse the tool-workpiece interface temperature in production in order to carry out subsequent laboratory tests of several alternative tribo-systems under realistic conditions. The analysis is based on a recently developed combined numerical-experimental approach (Ceron et al., 2014). The experimental measurements of temperature in a few points of the tool are the inputs to the thermal modelling of steady-state conditions. The determined temperature distribution in the tool is used as a boundary condition in the subsequent thermo-mechanical analysis. In this way, the thermo-mechanical model simulates the stage when the production is already in a steady-state condition, thereby avoiding the simulation of the preceeding hundreds of strokes, which leads to steady-state conditions. The model is validated by experimental measurements, and it is furthermore tested with and without inclusion of frictional heating to evaluate the reliability of the thermo-mechanical coupling. Finally, the sensitivity of the model is examined to estimate the effect of the initial steady-state temperature distribution of the tool, varying friction coefficient and heat transfer coefficient.

2. Experimental set-up

2.1. Process conditions

The industrial ironing operation is performed on a Raster 400 ton mechanical press with link drive operating at 38 spm. Fig. 1a and b shows an outline of the ironing operation.

The ram speed of the eccentric press can be adjusted by introducing a linkage system. Fig. 1c shows the speed with and without the link drive. Negative ram speed corresponds to the punch moving downwards. Introducing the link drive has the advantage of decreasing the