Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 18
ISSUE 1-2
September-October
2006

The tribological state test in metal forming processes using experiment and modelling

M. Jurkovic [a], Z. Jurkovic [a,*], S. Buljan [b]
[a] Department of Industrial Engineering and Management, Faculty of Engineering, University of Rijeka, Vukovarska 58, HR-51000 Rijeka, Croatia
[b] Federal Ministry of Energy, Mining and Industry, Adema Buca 34, BA-88000 Mostar, Bosnia and Herzegovina
* Corresponding author: E-mail address: zoran.jurkovic@ri.t-com.hr

Received 15.03.2006; accepted in revised form 30.04.2006

Manufacturing and processing

ABSTRACT

Purpose: of this paper is test of the tribological state in metal forming processes with main aims the determination of state on the tool contact surface (contact stresses and friction coefficient) friction coefficient modelling and simulation and to present the original method of defining contact stresses tf and pn and coefficient of contact friction m.
Design/methodology/approach: of this research is review of contact stresses determination methods, general principles of stochastic modelling, experimental friction test and modelling, examples tribological state test and simulaton by deep drawing and drawing processes. Main achievement are: original experimental identification of contact stresses, original experimental of tools for measurement of contact stresses, mathematical model for defining the tribological state. Application methods of this research are: experimental, tribological state test in forming processes by means of experiment and modelling, statistical and direct contact stresses determining method.
Findings: experimental and stochastic modelling of tribological parameters of the forming processes and verification of mathematical model. The tribological state test is performed on the basis of experimental investigations and stochastic modelling.
Research limitations/implications: modelling and optimization of tool geometry and selection of optimal lubricators, development experimental methods in the determination of contact stresses, etc.
Practical implications: Results of investigations in processing conditions show that the desired effects can be achieved: increased durability of tools 20-40%, reduced stagnation time in the machining process 20-30%, increase on the productivity of the forming process 15-30% and less energy consumption up to 15%.
Originality/value: of this paper is obtained original mathematical model for defining coefficient contact friction and contact temperature on the contact surface of tool. Also, is obtained original experimental tool for measurement of contact stresses.
Keywords: Plastic forming; Deep drawing; Tribological state; Sensor tool

1. Introduction

The tribological state depends on the material characteristics of workpiece and tool, geometry of tool working surface (stiffness, microgeometry of contact surfaces, die clearance, etc.), lubrication, technological parameters of machining process (velocity, degree and temperature of deformation) and type of used machine. The tribological state test by forming processes is performed on the basis of experimental researches and modelling by means of experimental results (stochastic modelling). The tribological state on the contact surface between the tool and workpiece can exactly be determined based on contact stresses (normal and tangential), coefficient of friction and contact temperature on the tool. The knowledge of intensity and distribution of the contact stresses and friction coefficient over the die surface in metal forming processes is of importance both from the theoretical standpoint of process analysis and the die design. The friction minimization by forming processes is reflected in: tool life increased, stagnation time reduced, increased of the machining process productivity, less energy consumption, less consumption of tools and less production costs. Thus, in the paper the tribological state of deep drawing and drawing processes analysed by using the experimental method and stochastic modelling technique [1-15].

2. Experimental test of tribological state by deep drawing process

The identification of forming process is performed analysis on the basis of known theoretical data, experimental investigations and simulation of state on the contact surface between tool and workpiece (Fig. 1).

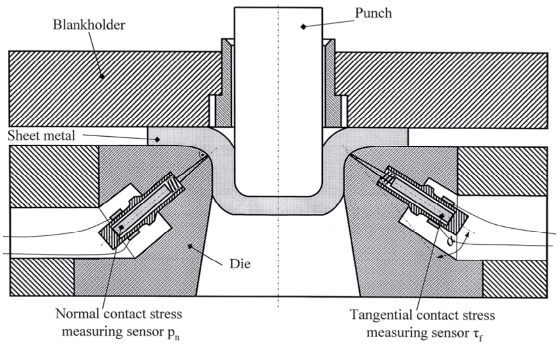

Fig. 1. Experimental tool for measurement of contact stresses in deep drawing process

2.1. Experimental sensor tool for the contact stresses measurement

The measurement procedure and appropriate tools have been original developed for determination and analysis of contact stresses in deep drawing process [2-5,8].

The direct contact stresses determining method has been analyzed and on the basis of this, a sensor has been conceptually elaborated and designed for normal stresses (p_n – sensor pin 1) and tangential contact stresses (τ_f – sensor pin 2) measurement (Fig. 2). The contact stresses were measured by means of pins with tensiometer transducers, where force on the pin 1 is F_{n1} for $\theta = 90°$ and on the pin 2 is F_2 for $\theta < 90°$ or $\theta > 90°$.

On the sensor pin 1: $F_{n1} = p_{n1} A$ (1)

On the sensor pin 2: $F_2 = F_x + F_f = p_x A + \tau_f A \tan\alpha$, that is,

pressure: $p_2 = p_x + \tau_f \tan\alpha$ or $p_x = p_2 - \tau_f \tan\alpha$, i.e. $p_{n1} = p_x$ (2)

The tangential contact stress (contact friction stress):

$$\tau_f = \frac{p_2 - p_x}{\tan\alpha} \qquad (3)$$

The Coulomb´s law is valid in consideration of $\mu = f(\tau, p)$, where τ is the tangential stress (contact friction stress) and p is the normal pressure on the contact area.

Therefore, the contact friction coefficient on die radius is:

$$\mu = \frac{\tau_f}{p_{n1}} = \frac{\tau_f}{p_x} \quad \text{or} \quad \mu = \frac{F_2 - F_{n1}}{A \tan\alpha \; p_{n1}} \qquad (4)$$

The contact friction forces are: $F_{f1} = \tau_f A$ and $F_{f2} = \tau_f \dfrac{A}{\cos\alpha}$.

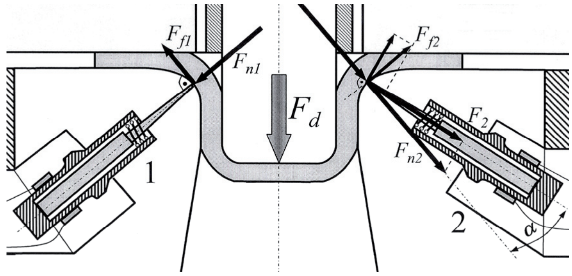

Fig. 2. Experimental tool set-up

2.2. Experimental conditions and results

The experiment was performed on the sheet metal DIN St14, material thickness s=0.8 mm and yield strength σ_f = 208-220 N/mm^2. Experiment were carried out by hydraulic press HSO-1-63 with following features: punch velocity v=10 mm/s, maximal force 630kN, maximal stroke 250mm. Blankholder pressure p_d = 1.5 N/mm^2.

Table 1.
The friction coefficient values

Lubricant and sheet surface treatment	degree of deformation $\varphi = ln\ A_x/A_1$				
	0.33	0.40	0.50	0,60	0.67
dry friction (S)	0.138	0.144	0.150	0.165	0.180
non phosphate sheet surface and deep drawing oil (U)	0.11	0.115	0.120	0.124	0.130
phosphate sheet surface and deep drawing oil (F+U)	0.074	0.078	0.082	0.085	0,089
non phosphate sheet surface and molybdenum disulfide (MD)	0.036	0.040	0.044	0.047	0.054
phosphate sheet surface and molybdenum disulfide (F+MD)	0.015	0.016	0.018	0.025	0.028

A_x – changeable cross section depends on blank diameter D_0, A_1 = const for d_1 = const. Highlight values of friction coefficient used by modelling (Table 1)

Intensity of the deep drawing friction coefficient was carried out by the five different contact state between sheet and tool, that is: fragmentary dry friction (S), non phosphate sheet surface and deep drawing oil (U), phosphate surface and deep drawing oil (F+U), non phosphate sheet surface and molybdenum disulfide (MD), phosphate sheet surface and molybdenum disulfide (F+MD). Depends on lubricant, friction coefficient values have been determined by contact stresses measurement. The obtained results of friction coefficient depend on lubricant and degree of strain are presented in Table 1.

2.3. The friction coefficient modelling

The experiment aim is to define adequate mathematical model which is used to determine the influence of independent parameters (input parameters x_1, x_2), at friction coefficient (output parameters $Y = \mu$), as it is shown at Fig. 3. For independent parameters, the following are selected: lubricant *(λ)* and degree of deformation *(φ)*.

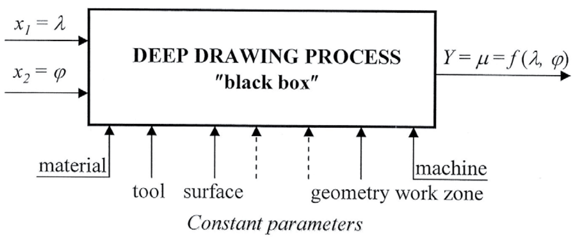

Fig. 3. The friction modelling scheme

Coefficient of friction is modelled by means of second order polynomial with interactions for two input parameters, that is:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_{11}X_1^2 + b_{22}X_2^2 + b_{12}X_1X_2\,, \tag{5}$$

After check of factors significance model has the following coded form:

$$Y = 0{,}08 + 0{,}04233X_1 + 0{,}004651X_2 + 0{,}001622X_1^2 \tag{6}$$

or in physical quantities:

$$\mu = -0{,}01485 + 0{,}066237\lambda + 0{,}04651\varphi + 0{,}00536\lambda^2 \tag{7}$$

Multiple regression coefficient R = 0,99 shows that friction model (7) decribes accurately enough experimental results within range of experiment (Table 2.)

2.4. Simulation of friction coefficient

Because it is very important to make right decision at the right time, and the time shortages, it has been developed own software MODSIM (Modelling and SIMulation).

MODSIM has an ability to form adequate mathematical model using input values of process parameters and experimentally obtained output values. Using on this way obtained mathematical model, and varying the input values of process, it is possible to get output values of process as well as to optimize process with model simulation. Using previously developed MODSIM software it is possible to carry out 2D simulation of the friction coefficient model for the various values of parameters *(λ, φ)*. For the purposes of 3D simulation, link between MODSIM and MATLAB® has been established and graphs are given on Fig. 4.

3. Conclusions

The performed research shows that the experimental methods (sensor pins) and modelling can be successfully used for defining the tribological state of processes (contact friction coefficient) in the metal forming processes. By means of a special measuring instrument experimental research of mechanical load on contact surface of deep drawing tool was carried out (τ_f, p_n).The experimental-mathematical method described shows that the normal contact pressure and specific frictional force (tangential contact stress) can exactly be determined on the contact surface of tool and workpiece, which is significant for the proper tool construction, less energy consumption and less production costs.

Table 2.
Experimental results and comparison of experimental values with friction coefficient values by model (7)

Test №	Input parameters values		Coded parameters values		Experimental measured values of friction coefficient	Calculated values of friction coefficient by model (7)
	λ^*	φ	X_1	X_2		
1	0.45 (MD)	0.40	-1	-1	0.040	0.0346
2	1.55 (U)	0.40	1	-1	0.115	0.119
3	0.45 (MD)	0.60	-1	1	0.047	0.0439
4	1.55 (U)	0.60	1	1	0.124	0.128
5	1.0 (F+U)	0.50	0	0	0.082	0.08
6	1.0 (F+U)	0.50	0	0	0.081	0.08
7	1.0 (F+U)	0.50	0	0	0.075	0.08
8	1.0 (F+U)	0.50	0	0	0.083	0.08
9	1.0 (F+U)	0.50	0	0	0.079	0.08
10	0.22 (F+MD)	0.50	-1.4142	0	0.018	0.0233
11	1.78 (S)	0.50	1.4142	0	0.150	0.143
12	1.0 (F+U)	0.35	0	-1.4142	0.074	0.0734
13	1.0 (F+U)	0.65	0	1.4142	0.089	0.0865

* $\lambda_{MD} = \dfrac{\mu_{MD}}{\mu_{F+U}} = 0{,}49\,(0{,}45)$; $\lambda_U = \dfrac{\mu_U}{\mu_{F+U}} = 1{,}54\,(1{,}55)$; $\lambda_S = \dfrac{\mu_S}{\mu_{F+U}} = 1{,}86\,(1{,}78)$; $\lambda_{F+MD} = \dfrac{\mu_{F+MD}}{\mu_{F+U}} = 0{,}22$

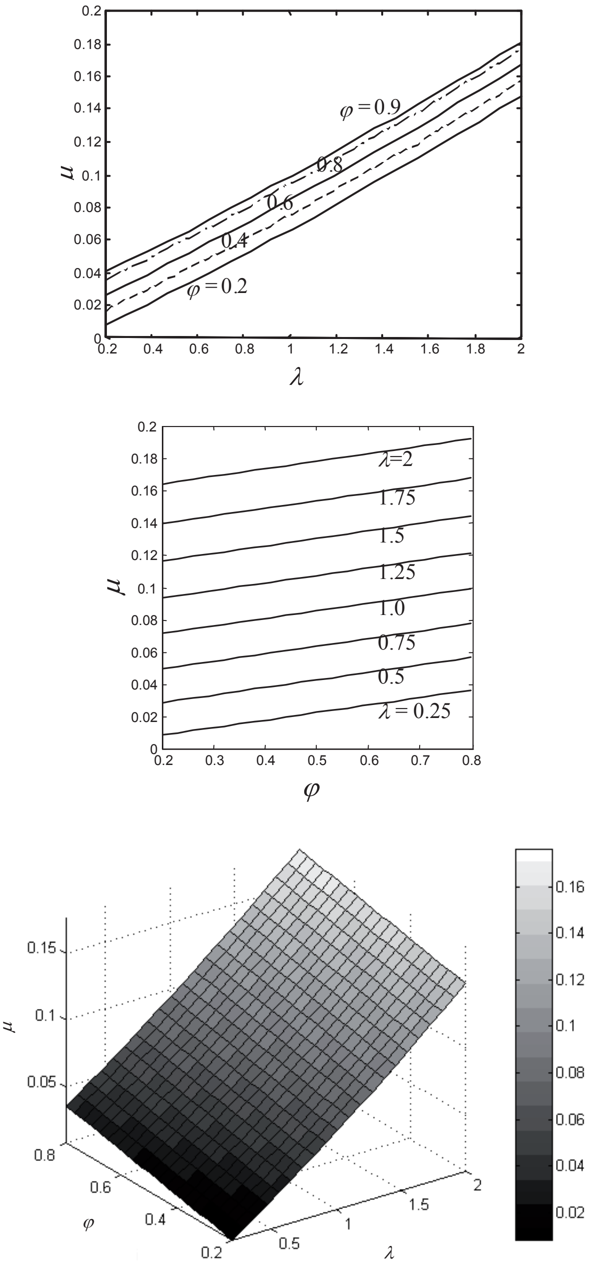

Fig. 4. 2D&3D simulation graphs of friction coefficient model (7)

Mathematical models for tribological parameter (friction coefficient) has shown as highly adequate and reliability. Also. multiple regression coefficients have shown as very high R_{μ} = 0.99 for friction coefficient. The obtained results and mathematical model indicate that the coefficient of friction is depend on the strain and type of used technological lubricant. Results of investigations in working conditions show that desired effects can be achieved: increased durability of tools 20-40%. reduced stagnation time in the machining proces 20-30%. increase of the productivity of the machining process 15-30% and less energy consumption up to 15%.

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