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Analytical model for friction coefficient determination in hydroforming of thin-walled tube elements

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1. Introduction

The metal forming processes implies processing without cutting removal, giving the material a wanted shape by using different methods of plastic forming. Industrial branches where the changes occur with the introduction of the new technologies in a very short period are automobile and aviation industries, because the securing and ergonomic criteria had to be achieved. These demands initialized setting of the new productive philosophy, which is based on a modern production, so-called unconventional processes like plastic forming with an incompressible fluid (Fig. 1). With the knowledge implementation, in this field, the new different procedures of hydraulic plastic forming developed like: deep drawing, bending, stretching, extrusion, expansion, connecting etc. All these processes are greatly applied in automobile and other branches of industry.

This paper provides researches and analyses of hydroforming of thin-walled tube elements [1-10]. In metal processing with hydroforming, the friction between a die and workpiece significantly influences on a material flow and presents the crucial parameter in determining of work pressures in hydroforming process.

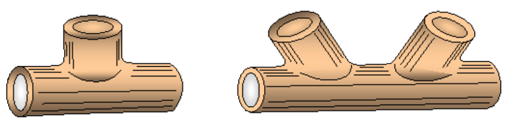

Fig. 1 Shape of the tubular elements produced by hydroforming processes

The conditions of the contact friction are constantly changing during the hydroforming process and present a complex analytical problem, which complicates obtaining of a reliable mathematical friction model. It is completely understandable that even the tribological mechanism in model experiments is alike, and also complicated, like in real processes.

The friction research of the contact between material and die for hydroforming is of a significant importance considering the duration of the die, product accuracy and synchronous device work for hydroforming. A large number of researches are dealing with this problem, even though the hydroforming processes are considered as processes with decreased or friction of a small intensity.

2. Friction influential zones in tube hydroforming

In tube hydroforming process the friction influence is significantly important on overall functioning of forming force. The areas of friction influence in fluid forming process (Fig. 2) can be separated on different influential zones.

For the purpose of easier analytical model understanding of friction coefficient determining between the workpiece-tube and die in hydroforming forming process, it is necessary to differ friction zones shown in Fig. 2. There are three zones: expansion zone, transition zone and guided zone.

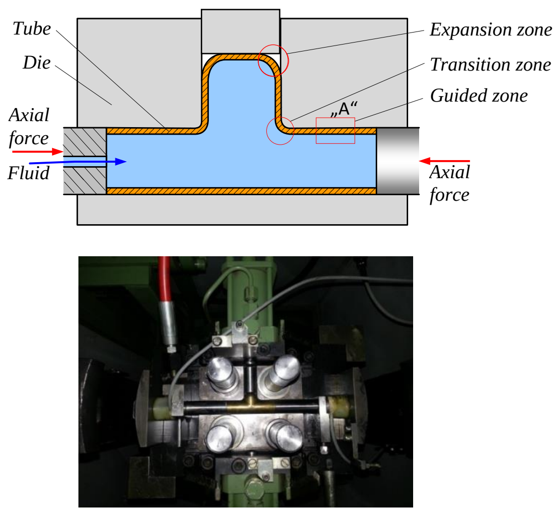

Fig. 2 Friction zones in tube hydroforming

The pressure of an incompressible fluid in a tube has to be in allowed limits. Any other deviation leads towards an error in tube hydroforming process. The increased pressure p_{max} can cause protractions of tube wall in a cross section of a bulge part, and consequently the bulge can burst/tear in tube hydroforming [12, 13].

Due to the material flow in expansion zone, stress σ_θ of tube wall is caused by starching of material. Therefore, the stress σ_z and σ_ϑ are caused by material compression all over the tube length, while stress σ_θ changes from compression on tube ends till the stretching in transition zone.

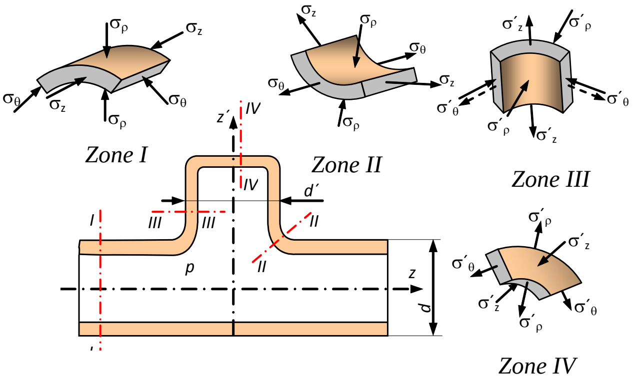

Fig. 3 Zones scheme of stress states in zones I, II, III, IV [1]

Theoretical researches imply the calculation of fluid pressure and axial force for a shape part in Fig. 3. The fluid tube pressure that forms the T shape tube is determined with an equation in a form [11-15]:

$$p=\frac{\beta ks\left(\frac{1-\frac{R_0}{\rho}}{R_\rho}+\frac{1}{R_\theta}\right)-\frac{sR_0F_a}{R_\rho \rho A}}{1+\frac{s}{R_\rho}\left(1+\frac{R_\rho}{\rho}\right)+\frac{s}{R_\theta}}. \tag{1}$$

The force necessary for plastic deformation (compression) of a tube is calculated with the equation:

$$F_{pd}=\pi\left\{\begin{array}{l} p\frac{d^2-\left(d-2s_i\right)^2}{4}+ \\ \beta\sigma_v\left[\frac{3}{4}\left(d-s_i\right)s_i+\frac{d^2}{8}ln\frac{d}{d-2s_i}\right]\end{array}\right\}. \tag{2}$$

Researches of friction influence in the guided zone of the tube part have been analysed by a group of researchers (Schmoeckel and others), while at the same time Dohrmann has been researching all zones of friction influence for a selected tube form.

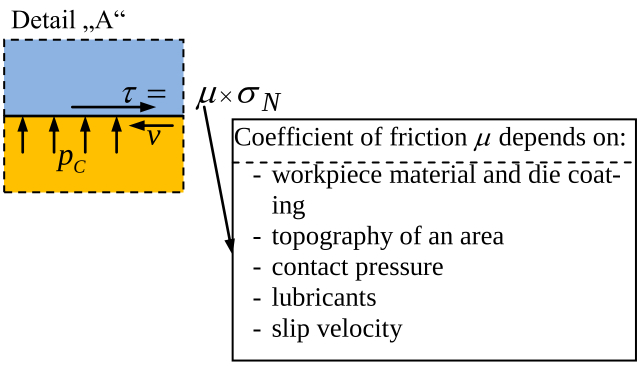

Fig. 4 Influential friction parameters in hydroforming

With the friction analysis between a tube and die in hydroforming differently then of an authors [13-15], a new approach of analytical determining of friction coefficient has developed. In Fig. 2 the guided and expansion zones in tube hydroforming have been shown. In order to approach to analytical modelling of friction coefficient, it is necessary first to analyse contact between the workpiece-tube and die (detail „A“). With the analysis of a detail „A“ (Fig. 4) it is obvious that the friction coefficient and contact stresses depend on valuation of influential parameters in hydroforming. The authors [15] carried out the analytical model of friction coefficient defining through the stress analysis in different zones, like it is shown; they also determine the friction force in an experimental way. After the analysis of stress and strains all over the tube size, authors come to the analytical expression for the friction coefficient:

$$\mu=\frac{(2\alpha-1)s_0}{L}ln\left(\frac{F_t}{4\pi r_0 p_{uc}(\alpha-1)s_0}+1\right), \tag{3}$$

where F_t is friction force which is determined experimentally [15], L is tube length, r_0 is external radius, α is contact angle.

The analytical model of friction coefficient determining by G. Ngailu [15] is defined through the stress analysis in zones, and is carried out for the guided zone, which is expressed with the Eq. (3). When determining the friction coefficient, by G. Ngailu, the friction force is determined experimentally. This model also contrasts the real model, considering that the expansion zone is not taken into account. If analytical models of friction coefficient determining in hydroforming between the workpiece and die by authors [13, 14] are analysed, it can be concluded that the solutions for friction coefficient μ take into account the increase of the contact pressure caused by load on outer diameter, while solutions [14] assuming that the stresses are in contact of the tube and die $(\sigma_k)\sigma_k = p_{uc}$ doesn't take into account. This way of analytical model determining of friction coefficient refers to the deformation of symmetrical workpiece where the expansion zone is not taken into account, and contrasts with the real deformation model in tube hydroforming.

Analyzing the friction between the tube and the die in hydroforming differently than the above authors analyzed, we come to the new analytical model for friction coefficient determination in hydroforming of thin-walled tube elements. Fig. 5 shows an analytical approach which is taken into account guided zone and free expansion zone of workpiece.

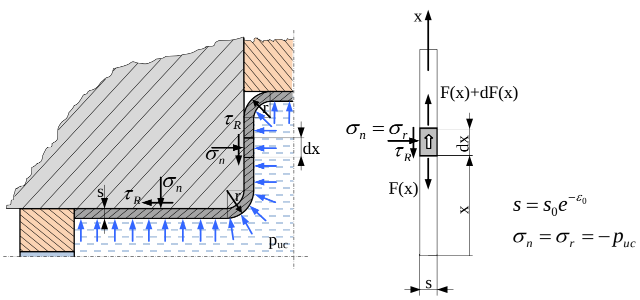

Fig. 5 Analysis of forces and stresses in hydroforming of thin-walled tube elements

Taking into account the equations [16] and respect to the Hooke's law over the equilibrium conditions of the infinitely small element dx, following equations are obtained:

$$\left.\begin{aligned}
&\frac{d\,\sigma_\theta}{d\,x} = \frac{\mu}{s}\,p_{uc};\\
&\sigma_\theta = C\beta^{n+1}\varepsilon_\theta^n - p_{uc};\\
&\frac{\mu\,p_{uc}}{s} = C\beta^{n+1} n\,\varepsilon_\theta^{n-1}\frac{d\theta}{d\,x}.
\end{aligned}\right\} \tag{4}$$

After analytical procedure, we come to the new analytical model of the friction coefficient between the workpiece and die for thin-walled tube elements which is very significant for hydroforimng processes:

$$\mu = \frac{p_{uc}\,x}{Ase^{-\varepsilon_\theta} - Bs_0 e^{-\varepsilon_{sym}}}, \tag{5}$$

where $A = C\left(\frac{2}{\sqrt{3}}\right)^{n+1}\varepsilon_\theta^n - p_{uc}$, $B = C\left(\frac{2}{\sqrt{3}}\right)^{n+1}\varepsilon_{sym}^n - p_{uc}$,

$C = K = R_m\left(e/n\right)^n$ is constant depending on a material type, n is hardening curve exponent of third order, μ is friction coefficient between the workpiece and die; ε_θ is equivalent strain in direction of θ, ε_{sym} is equivalent strain direction of radius r, x is observed contact length of die and workpiece.

In this paper new approach to analytical model of friction coefficient determining in hydroforming has been analysed, where the guided zone and expension zone has been taken into account, and with the equation derived (5).

With the analytical model of friction coefficient determining, it is in the function of the dimensions: workpiece material, workpiece wall thickness, fluid pressure and deformation ratio. The analytical model for friction coefficient determining in hydroforming is practical for application and describes a real model of hydroforming. Direct measuring of contact friction between the die and workpiece in plastic forming process can be carried out with the application of the needled sensors.

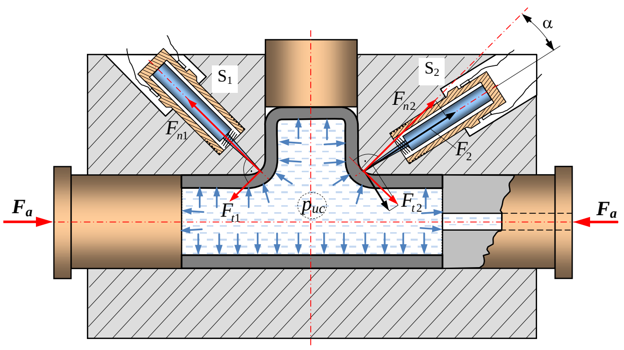

Fig. 6 Position of needled sensors in hydroforming process

This method of experimental measuring is one of the most reliable and accurate method, because the contact friction is directly measured by sensors placed into the die, through which normal or tangential stress has been measured. The Fig. 6 presents the way of placing the needled sensors of contact friction measuring in T part hydroforming process.

The needled sensors can be successfully applied in other processes of plastic forming. With the application of experimental way of contact friction measuring by the needled sensors, the information about tribological state between workpiece and die occur. Though, this method is very expensive and demands sensor installation into a die.

3. Conclusions

In the process of hydroforming, the friction between a die and workpiece significantly influences on a material flow and presents the crucial parameter in determining of work pressures in hydroforming process. The conditions of the contact friction are constantly changing during the hydroforming process and present a complex analytical problem, which complicates obtaining of a reliable mathematical friction model. A key factor in physical simulation of process is an election of an adequate lubricant, in order to establish conditions of similarity of the real and model process, and validity of modelling results.

The contact of a workpiece and die for hydroforming in a work process manifests with the friction force which has an influence on: axial force, axial punch feed and workpiece wall thickness. The stress-strain state and their disposition during the tube hydroforming are foundation where the friction influence in tube hydroforming is based on. Theoretical researches imply the calculation of fluid pressure and axial force. The fluid tube pressure that forms the T shape tube is determined with the Eq. (1), while the force necessary for plastic deformity of tube is given with the Eq. (2). With the friction analysis between a tube and die in hydroforming, a new approach of analytical determining of friction coefficient has been developed.

The new approach to analytical model of friction coefficient determining in hydroforming has been analysed, where the guided zone and the expansion zone has been taken into account, and with the equation derived (5). With the analytical model of friction coefficient determining, it is in the function of next dimensions: workpiece material, workpiece wall thickness, fluid pressure and deformation ratio.

The analytical model for friction coefficient determining in hydroforming is practical for application and describes a real model of hydroforming. Direct measuring of contact attrition between the tool and preparation in plastic forming process can be carried out with the application of the needled sensors, like it is shown in Fig. 6.

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PLONASIENIŲ VAMZDINIŲ ELEMENTŲ HIDRAULINIO FORMAVIMO TRINTIES KOEFICIENTO ANALITINIS MODELIS

R e z i u m ė

Naujos technologijos sparčiausiai diegiamos automobilių ir aviacijos pramonėje, nes jos yra siejamos su saugumo ir ergonomikos kriterijais. Šie reikalavimai paskatino kurti naują gamybos filosofiją, kuri siejama su modernia gamyba – plastikų formavimu ir modeliavimu nespūdžiais skysčiais.

Vamzdžių hidraulinis formavimas ypač paplito per pastaruosius penkerius metus ir laikomas sparčiai besivystančia technologija. Šiame straipsnyje pateikiami plonasienių vamzdžių elementų tyrimų ir analizės rezultatai. Kontaktuojant ruošiniui ir presui hidraulinio formavimo metu pasireiškia trinties jėgos. Tai verčia analizuoti T formos vamzdžio deformacijos formavimo metu zonas. Pasiūlytas trinties tarp vamzdžio ir preso koeficiento pokyčio analitinis modelis. Šio straipsnio tikslas – pateikti naujo trinties koeficiento nustatymo formuojant plonus vamzdžių elementus analitinio modelio išraišką, kuri realiausiai apibūdintų procesą. Straipsnyje aprašomas adatinio jutiklio įrengimo, matuojant kontaktinę trintį T formos vamzdžio hidraulinio formavimo metu, eksperimentas.

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ANALYTICAL MODEL FOR FRICTION COEFFICIENT DETERMINATION IN HYDROFORMING OF THIN-WALLED TUBE ELEMENTS

S u m m a r y

Industrial branches where the changes occur with the introduction of the new technologies in a very short period are automobile and aviation industries, because the securing and ergonomic criteria had to be achieved. These demands initialized setting of the new productive philosophy, which is based on a modern production like plastic forming and modelling with an incompressible fluid.

A tube hydroforming got a significant role in the last five years and is considered as a technology of rapid development. This paper provides researches and analyses of hydroforming of thin-walled tube elements. A workpiece and die contact for hydroforming in a work process manifests with the friction force which has an influence on: axial force, axial punch feed and workpiece wall thickness.

The stress-strain state and their disposition during the tube hydroforming are foundation where the friction influence in tube hydroforming is based on. It provides an analysis of deformation zones and friction in T shape tube hydroforming. An analytical model of friction coefficient change in hydroforming between a tube and die has been carried out. The main objective of this paper is to suggest new analytical model for friction coefficient determination in hydroforming of thin-walled tube elements which describes process the most realistically. This paper provides an experimental way of needle sensor setting in measuring of the contact friction in T shape tube hydroforming.

Keywords: friction, thin-walled tubes, analytical model, hydroforming.

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