

UDK 621.774.77:621.7.016.3

## Simuliranje procesa rotacijsko simetričnega preoblikovanja cevi z notranjim tlakom in aksialno pomično matrico

### Computer Simulation of Axial Symmetric Tube Bulging Under Inside Pressure and Axial Compression

JANEZ PIPAN

*Razvoj računalnikov zlasti cenovno dostopnih delovnih postaj in osebnih računalnikov, skupaj z izpopolnjevanjem komercialnih programskih paketov za opravljanje nelinearnih analiz po metodi končnih elementov, ponuja vse več možnosti za preučevanje in optimiranje preoblikovalnih procesov na podlagi računalniškega simuliranja. V primeru obravnavanega postopka rotacijsko simetričnega preoblikovanja cevi z notranjim tlakom in aksialno pomično matrico se je izkazalo, da z analitičnim prijmom ni mogoče zajeti vseh vplivov, ki so odločilni za njegov potek. Določanje tehnoloških parametrov in optimiranja procesa sta bila zato vezana na eksperimentiranje, ki pa je v pogojih maloserijske izdelave gospodarno nesprejemljivo. V prispevku je opisan numerični model procesa, izdelan z uporabo programa za računanje po metodi končnih elementov ABAQUS ter njegova eksperimentalna potrditev, opravljena v Laboratoriju za preoblikovanje na Fakulteti za strojništvo Univerze v Ljubljani.*

*The recent development of computers, especially workstations and personal computers on the one hand, and commercially available FEM programmes for nonlinear analyses on the other, offers more and more possibilities for research and optimisation of metal-forming processes based on computer simulations. For axial symmetric tube bulging under inside pressure and axial compression it was found that all the influences that are decisive for the process course, cannot be considered by an analytical approach. Proper values of different process parameters were therefore determined experimentally, which is rather expensive and often unacceptable way for low batch production. The article deals with a numerical model for the process and its experimental verification.*

#### 0 UVOD

Postopki ekspandiranja cevi z notranjim tlakom in aksialnim pritiskom omogočajo preoblikovanje preprostih cevastih surovcev, tako da jih v osrednjem delu razširimo v želeno obliko, medtem ko ostanejo premeri koncev praviloma nespremenjeni. Izdelki so torej zaključene lupine določenega spektra oblik, ki jih odlikuje enakomerna debelina stene, nepretrgana vlaknasta struktura materiala ter plastična utrditev. Vse to prispeva k ugodnemu razmerju med nosilnostjo in maso, zaradi česar so ti postopki predmet intenzivnih raziskav, katerih namen je zlasti širjenje spektra dosegljivih oblik, optimiranje in povečanje zanesljivosti [1], [2], [3], [4], [5].

V primerjavi s starejšimi postopki preoblikovanja z medijem, pri katerih se kot obremenitev uporablja samo notranji tlak, v procesu deformacije pa prevladujejo membranske natezne napetosti, je prednost superponiranega aksialnega pritiska zlasti v tem, da so dosegljive deformacije bistveno večje,

#### 0 INTRODUCTION

Tube bulging processes, where inside pressure and axial compression are used as active loads, enable simple tube shaped workpieces to be formed in such a way that they are expanded in their middle region, while, as a rule, the ends remain unchanged. So the formed parts are closed shells inside a specific spectrum of achievable shapes. The distinctive features of such parts are: uniform wall thickness, fibrous structure and increased strength of the material, achieved by plastic hardening. As all these features contribute to a favourable load-capacity to weight ratio of such parts, these processes are the subject matter of research directed to the extension of the achievable shape spectrum, process optimisation and an increase of reliability [1], [2], [3], [4], [5].

In comparison with previously known tube forming processes in which only the pressure medium is used as an active load, so that membrane tension stresses prevail in the deformation process, the advantages resulting from superimposed axial compression are an increase of achievable deformations and a decrease of tube wall thinning.

stanjšanje stene cevi pa manjše. Želeni vpliv aksialnega pritiska je tem večji, čim večji je delež rezultirajočih aksialnih tlačnih napetosti v primerjavi z obročnimi nateznimi. Za ugodno velja npr. preoblikovanje pri napetostnem stanju čistega striga, kjer so pri zanemarljivo majhnih napetostih v smeri debeline, aksialne in obročne napetosti med seboj absolutno enake, debelina stene pa ostane nespremenjena.

Izmed obravnavanih postopkov se je do sedaj še najbolj uveljavil postopek aksialno nesimetričnega izbočevanja cevi, ki se uporablja za izdelavo različnih spojnih delov cevovodov, npr. kosi T [6], [7], [8]. K temu je poleg preprostejšega optimiranja procesa, pripomogla predvsem velikoserijska proizvodnja takih izdelkov, ki upravičuje nabavo dragih namenskih strojev. Drugi postopki so še v fazi razvoja, ki bo nedvomno prispeval k njihovi širši uporabi. Med slednje spada tudi postopek rotacijsko simetrično izbočevanje cevi z notranjim tlakom in aksialno pomicno matrico. Glede na razmeroma ceneno orodje (matrici), je ob predpostavki, da imamo na voljo ustrezni namenski stroj, ta postopek primeren tudi za maloserijsko proizvodnjo. Izkazalo pa se je, da je zaradi možnosti pojava tlačne nestabilnosti na eni strani, oziroma plastične na drugi, uspešnost tega postopka odvisna od ustrezne izbire začetnih parametrov in še posebej od izbranega poteka kombinacije oben obremenitev. Prepletjenost vplivov: oblike orodja, geometrijskih in snovnih parametrov cevi ter zunanje obremenitve je takšna, da poteka procesa analitično ni mogoče določiti. Pri optimirjanju procesa si sicer lahko pomagamo tudi s sistematičnimi preizkusi, ki pa so za maloserijsko proizvodnjo ekonomsko nesprejemljivi. Problem določanja poteka procesa in njegovo optimiranje sta torej velika ovira pri uporabnosti postopka.

Upoštevajoč nove možnosti, ki jih ponuja razvoj računalništva tako glede večanja zmogljivosti računalnikov kakor tudi izpopolnjevanja komercialnih programov, namenjenih za opravljanje nelinearnih analiz z metodo končnih elementov (MKE), je bilo reševanje problema [9] usmerjeno v cenejšo, računalniško simuliranje procesa. Z uporabo programa ABAQUS je bil izdelan numerični model, ki ga je bilo treba zaradi kompleksnosti problema tudi eksperimentalno preveriti.

## 1 OPIS POSTOPKA

Postopek rotacijsko simetričnega preoblikovanja cevi z notranjim tlakom in aksialno pomicno matrico je z značilnimi fazami prikazan na sliki 1. Značilno za prikazani postopek je, da del cevi, ki se trenutno preoblikuje, ni v neposrednem stiku z orodjem.

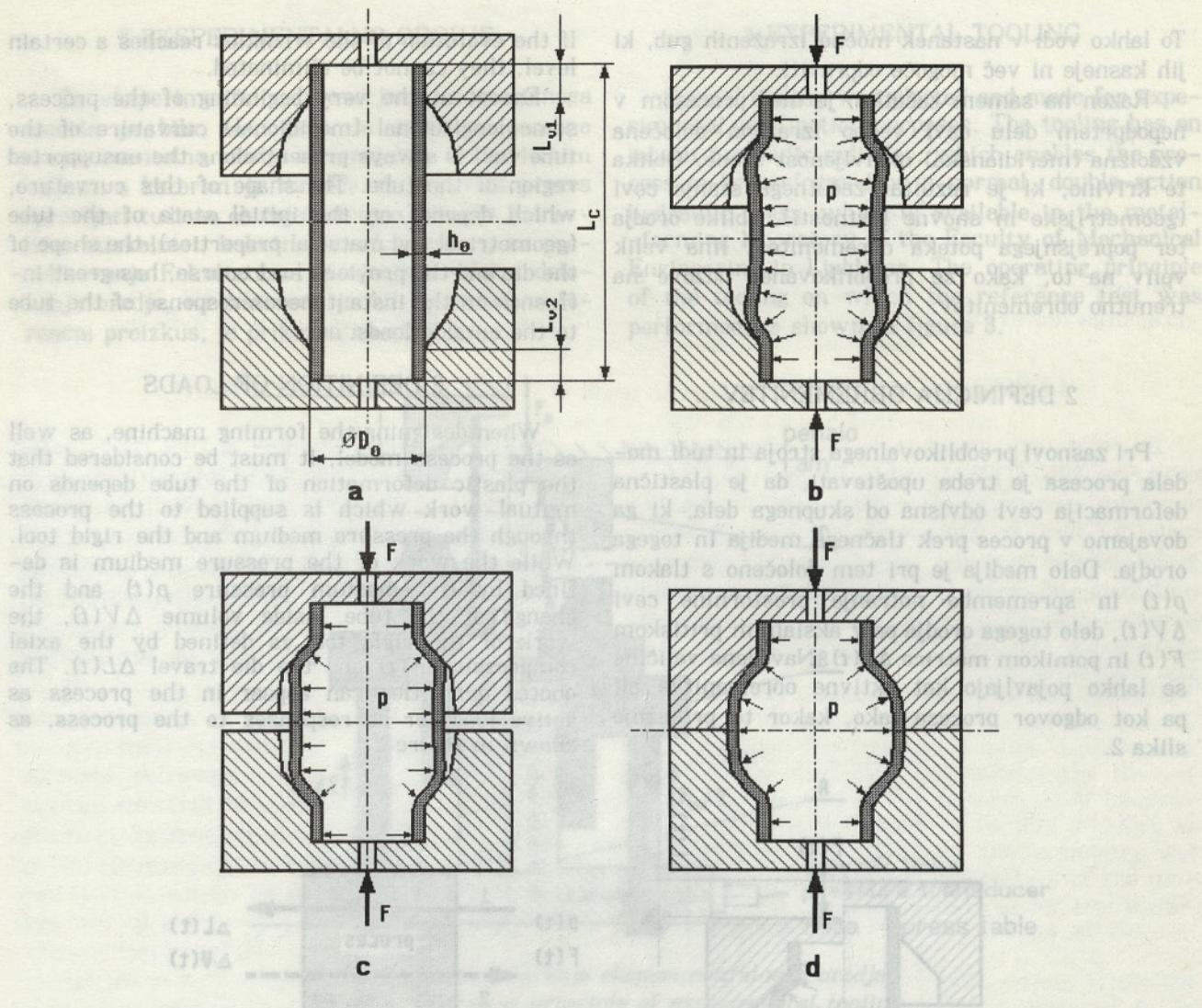
The desirable influence of the superimposed compression depends on the resulting ratio between the axial compressive stresses and the circumferential tensile stresses. Favourable stress conditions are considered to be those of pure shear, where with negligible stresses in the thickness direction the stresses in axial and circular directions are absolutely equal, so that the tube wall thickness is not affected.

The best known of the discussed tube forming processes is asymmetrical tube bulging, which is used in manufacturing T-pieces [6], [7], [8]. The economic reasons, arising out of mass production of these parts, have stimulated the development of special forming machines and process optimisation based on experimental research. Other processes are still in the phase of development, which will undoubtedly contribute to an increase in their applicability. One of these is the rotational symmetric tube bulging process, in which loading by a pressure medium and an axially thrusting die is applied. Since tooling for this process is relatively inexpensive, and assuming that a suitable special forming machine is available, this process is also suitable for medium and low-batch production. However, it has been shown that because of the possible occurrence of plastic instability on the one hand and pressure instability on the other, the success of forming depends on the proper choice of the initial process parameters and also on the combined load course. The complexity of the process, subjected to the combined influences of the die shape, geometrical and material parameters of the workpiece, as well as on arbitrarily chosen combination of active loads, is such that the process course can not be determined analytically. Process optimisation could be done by the help of systematic experimentation, but this method is unacceptable for low batch production. In terms of the usefulness of the process, the problem of its optimisation and determination of its course is therefore a great obstacle.

In view of the new possibilities which are offered by the development of computers, as well as commercially available FEM codes developed especially for nonlinear analyses [9], the solving of this problem was directed to less expensive computer simulations. A numerical model of the process was made using code ABAQUS. Because of the complexity of the problem, the model was subjected to experimental verification.

## 1 PROCESS DESCRIPTION

The process, with its typical phases is shown in figure 1. It is characteristic of this process that the part of a tube where the forming takes place is not in direct contact with a rigid tool surface.



Sl. 1. Postopek rotacijsko simetričnega izbočevanja cevi z notranjim tlakom in aksialno pomično matrico  
 a – začetno stanje, b – faza prostega izbočevanja cevi z vpetima koncema,  
 c – faza izbočevanja s postopnim naleganjem na steno matrice, d – končno stanje

Fig. 1. Axisymmetric tube bulging process using inside pressure and axial compression of a moving die  
 a – initial state, b – phase of free bulging of the tube with the ends fixed in the dies,  
 c – phase of bulging with progressive fitting to the die surface, d – final state

Ta del je največji na začetku procesa (sl. 1a), ko sta v stiku z orodjem samo vpta konca cevi. Med procesom se prosta dolžina s postopnim naleganjem cevi na steno matrice zmanjšuje tako, da pride v končni fazi kalibriranja do polnega naleganja (sl. 1d). Preoblikovanje poteka skoraj brez drsenja med orodjem in preoblikovancem, zato je vpliv trenja na proces in obrabo orodja majhen. Zaradi aksialnega nakrčevanja nepodprtrega dela cevi pa se po drugi strani pojavijo problemi, povezani s tlačno stabilnostjo procesa. Do tlačne nestabilnosti pride takrat, ko je odpor cevi proti vsiljenemu aksialnemu pomiku matric manjši pri gubanju stene kakor pa pri nakrčevanju.

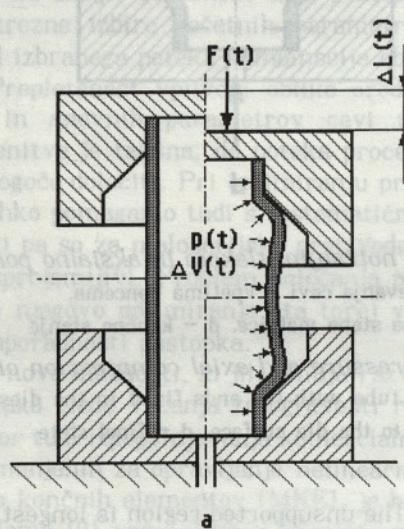
The unsupported region is longest at the beginning of the process (Fig. 1a), when only the two guided ends of the tube are in contact with the tool. During the process, as the tube bulge progressively fits the walls of the die cavity, this length reduces, so that a total fit is achieved at the end of the calibration phase (Fig. 1d). There is only negligible sliding between the tube and the die, so the influences of friction on the process and the wear of the tool is minimal. Because of the unsupported portion of the tube being upset, problems which are related to the pressure stability of the tube arise. The process is unstable when the resistance to the axial thrust of the die is lower if the tube shortens by folding than by upsetting.

To lahko vodi v nastanek močno izraženih gub, ki jih kasneje ni več mogoče odpraviti.

Razen na samem začetku, je med procesom v nepodprttem delu cevi vedno izražena določena vzdolžna (meridianska) ukrivljenost stene. Oblike te krivine, ki je rezultat začetnega stanja cevi (geometrijske in snovne lastnosti), oblike orodja ter poprejšnjega poteka obremenitev, ima velik vpliv na to, kako se preoblikovanec odzove na trenutno obremenitev.

## 2 DEFINICIJA OBREMENITEV

Pri zasnovi preoblikovalnega stroja in tudi modela procesa je treba upoštevati, da je plastična deformacija cevi odvisna od skupnega dela, ki ga dovajamo v proces prek tlačnega medija in togega orodja. Delo medija je pri tem določeno s tlakom  $p(t)$  in spremembijo notranje prostornine cevi  $\Delta V(t)$ , delo togega orodja pa z aksialnim pritiskom  $F(t)$  in pomikom matrice  $\Delta L(t)$ . Navedene veličine se lahko pojavljajo kot aktivne obremenitve ali pa kot odgovor procesa tako, kakor to prikazuje slika 2.

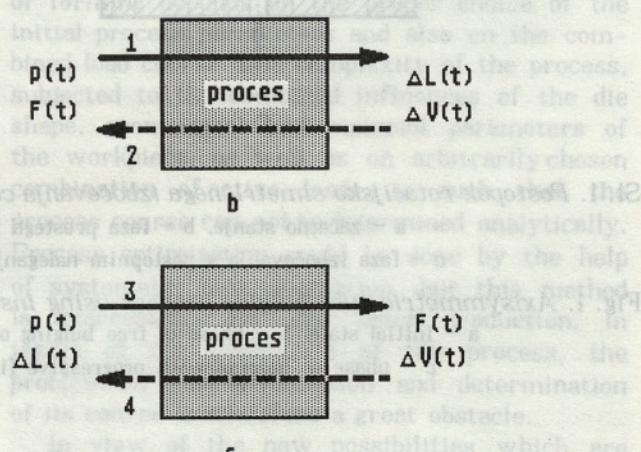


If the evolution of the wrinkles reaches a certain level, they cannot be eliminated.

Except at the very beginning of the process, some longitudinal (meridional) curvature of the tube wall is always present along the unsupported region of the tube. The shape of this curvature, which depends on the initial state of the tube (geometrical and material properties), the shape of the die and the previous load course, has great influence on the instantaneous response of the tube to the outside loads.

## 2 DEFINITION OF LOADS

When designing the forming machine, as well as the process model, it must be considered that the plastic deformation of the tube depends on mutual work which is supplied to the process through the pressure medium and the rigid tool. While the work of the pressure medium is defined by the medium pressure  $p(t)$  and the change of the tube inside volume  $\Delta V(t)$ , the work of the rigid tool is defined by the axial compression  $F(t)$  and the die travel  $\Delta L(t)$ . The quoted quantities can appear in the process as active loads or as responses to the process, as shown in figure 2.



Sl. 2. Kombinacije obremenitev pri procesu rotacijsko simetričnega preoblikovanja cevi z notranjim tlakom in aksialnim pritiskom

Fig. 2. Load combinations in axisymmetric tube bulging using inside pressure and axial compression

Za postopke preoblikovanja cevi s tlačnim medijem in aksialnim pritiskom se uporabljajo posebni preoblikovalni stroji, pri katerih je tlačni medij hidravlično olje, razpoložljivi tlaki pa dosegajo 800 do 1000 MPa. Ti stroji so numerično krmiljeni, kar povečuje njihovo prilagodljivost maloserijski proizvodnji.

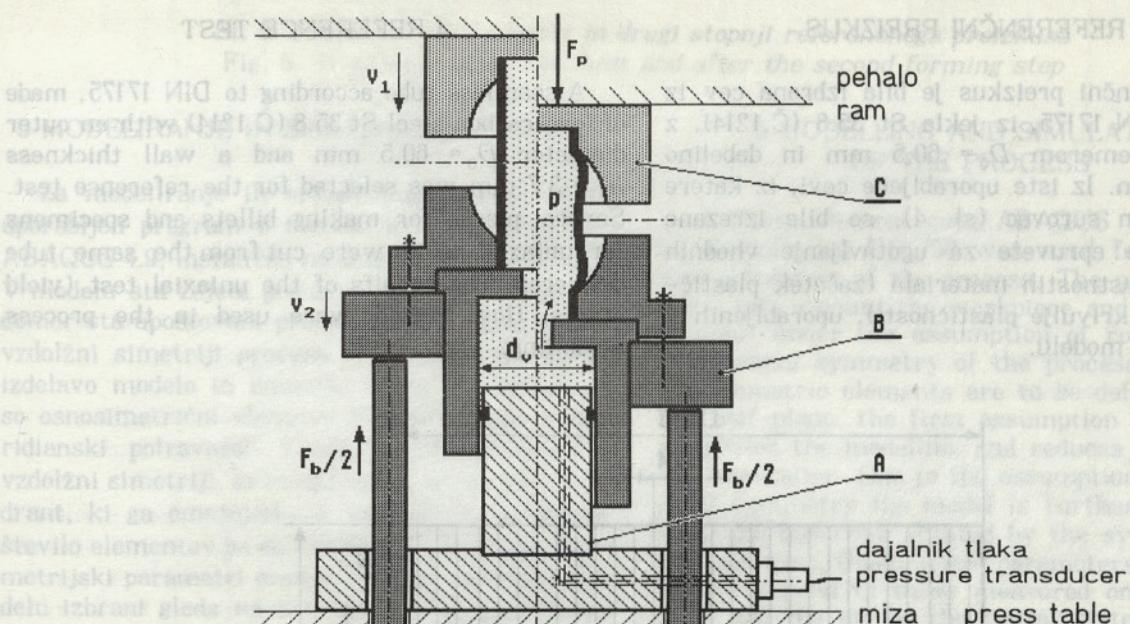
Special numerical controlled forming machines are available that fulfill the requirements of these processes and are flexible enough even for low batch production. The liquid medium pressure that can be achieved by pressure intensifiers, is 800 to 1000 MPa.

### 3 EKSPERIMENTALNO ORODJE

Za eksperimentalno preverjanje numeričnega modela je bilo zasnovano in izdelano posebno eksperimentalno orodje z vgrajenim hidravličnim valjem, s katerim je mogoče obravnavani proces opravljati tudi na običajni, dvojno delujoči hidravlični stiskalnici, kakršno ima Laboratorij za preoblikovanje Fakultete za strojništvo. Način delovanja orodja, na katerem je bil opravljen referenčni preizkus, je prikazan na sliki 3.

### 3 EXPERIMENTAL TOOLING

Special tooling was plotted and made for experimental verification purposes. The tooling has an inbuilt hydraulic cylinder, which enables the process to be performed on a normal, double-action hydraulic press, which is available in the metal-forming laboratory of the Faculty of Mechanical Engineering in Ljubljana. The operating principle of the tooling on which the reference test was performed, is shown in figure 3.



Sl. 3. Način delovanja eksperimentalnega orodja  
Fig. 3. Operating principle of experimental tooling

Orodje sestoji iz treh medsebojno pomicnih sklopov, pri čemer je sklop bata (A) pritrjen na mizo stroja, sklop spodnje matrice s hidravličnim valjem (B) navpično pomicen in podprt s silo blazine stroja ( $F_b$ ), sklop zgornje matrice (C) pa je pritrjen na pehalo. Za preizkuse sta bili uporabljeni matrici s simetrično oblikovanima gravurama, ki v sklenjeni legi oblikujeta kroglo s premerom 85 mm, z valjastima nastavkoma premera 61 mm in dolžino 9,81 mm.

Med silo pehalo  $F_p$  in silo blazine  $F_b$  ter tlakom medija  $p$  in aksialnim pritiskom  $F_c$  ki se prenaša z matrico neposredno na cev, veljajo naslednje zveze, dobljene iz statičnih ravnotežnih enačb:

$$p = \frac{4}{\pi d_v^2} (F_p - F_b) = k_1 (F_p - F_b) \quad (1)$$

$$F_c = F_p - \frac{\pi}{4} d_v^2 p = F_b + \left(1 - \frac{d_0^2}{d_v^2}\right) (F_p - F_b) \quad (2)$$

The tooling consists of three relatively movable parts. Part A (the piston with the lower bolster plate) is fixed to the press table, part B (the cylinder with the lower die) is movable up and down the piston and supported by the hydraulic cushion of the press ( $F_b$ ), while part C (upper die) is fastened to the ram. Symmetrically shaped dies were used for the reference test. The two dies are shaped in such a way that in the final stage of the process, when the dies are closed, their cavities form a sphere with a diameter of 85 mm, with two diametral cylindrical prolongations with diameters of 61 mm and lengths of 9,81 mm.

The following relations between the ram force  $F_p$ , the cushion force  $F_b$ , the forming pressure  $p$  and axial compression  $F_c$  were found from the equations of static equilibrium:

ali

$$F_c = F_b + k_2 (F_p - F_b) = F_b + k_3 p \quad (3)$$

V zgornjih enačbah pomenijo:

$$k_1 = \frac{4}{\pi d_v^2}, \quad k_2 = 1 - \frac{d_0^2}{d_v^2}, \quad k_3 = \frac{\pi}{4} (d_0^2 - d_v^2),$$

$d_0$  – začetni notranji premer cevi in  $d_v$  – premer vgrajenega hidravličnega valja.

#### 4 REFERENČNI PREIZKUS

Za referenčni preizkus je bila izbrana cev iz celega po DIN 17175, iz jekla St 35.8 (Č.1214), z zunanjim premerom  $D_0 = 60,5$  mm in debelino stene 3,7 mm. Iz iste uporabljeni cevi, iz katere je bil izdelan surovec (sl. 4), so bile izrezane tudi natezne epruvete za ugotavljanje vhodnih podatkov o lastnostih materiala (začetek plastičnosti, potek krivulje plastičnosti), uporabljenih v numeričnem modelu.

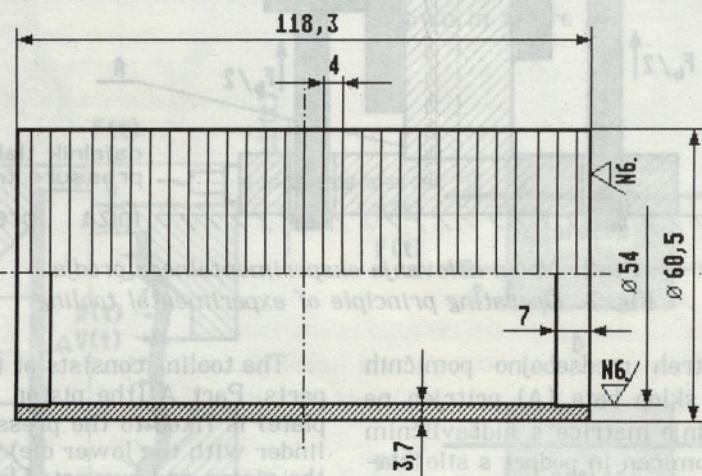
or

In the above equations:

$d_0$  – the initial inside tube diameter and  $d_v$  – the diameter of the inbuilt hydraulic cylinder.

#### 4 REFERENCE TEST

A seamless tube according to DIN 17175, made of low-carbon steel St 35.8 (Č.1214) with an outer diameter  $D_0 = 60.5$  mm and a wall thickness  $h_0 = 3.7$  mm was selected for the reference test. Several pieces for making billets and specimens for uniaxial tests were cut from the same tube delivered. The results of the uniaxial test (yield stress, flow curve) were used in the process modelling.



Sl. 4. Surovec za referenčni preizkus

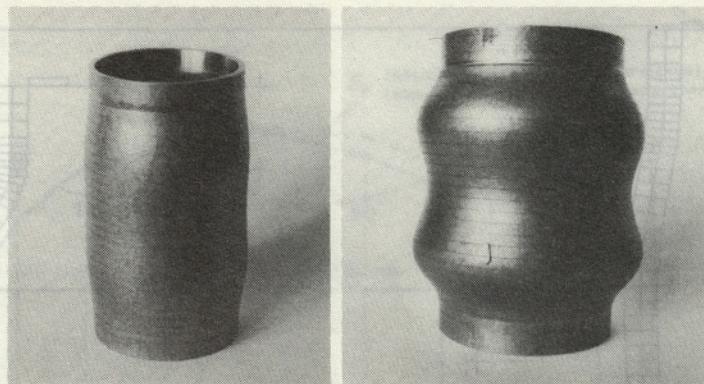
Fig. 4. The drawing of the billet for the reference test

Na surovcu sta bila mehansko obdelana samo konca cevi, ker sta zaradi pravilnega naleganja in tesnjenja, zahtevani vzporednost in gladka površina. Poleg tega so bile na zunani površini, simetrično glede na sredino cevi po vsej dolžini, z razmikom 4 mm, zarisane tanke krožne raze, namenjene merjenju sprememb oblike na posameznih mestih vz dolž cevi.

Preoblikovanje je bilo opravljeno v dveh zaporednih stopnjah, pri čemer so bili sproti merjeni potek tlaka, sile blazine in pomika matric. Obliki cevi po prvi in drugi stopnji preoblikovanja, ki sta prikazani na sliki 5, sta bili izmerjeni posebej, zunaj orodja.

Only the ends of the billet were machined, since the two faces must be parallel and smooth to achieve an uniform contact and reliable sealing during the forming process. In addition, parallel circular marks with a 4 mm pitch were cut all along the outside surface of the billet. The purpose of these marks, which coincide with the nodes of the undeformed net, is to enable measurement of local deformations on the deformed tube.

The tube forming, with on-line measurement of the forming pressure, the cushion force and the die travel, was done in two steps. The deformed shapes were measured separately after each step (Fig. 5), out of the tooling.



Sl. 5. Preoblikovanec po prvi in drugi stopnji referenčnega preizkusa  
Fig. 5. Workpiece after the first and after the second forming step

## 5 MODELIRANJE IN SIMULIRANJE PROCESA

Za modeliranje in simuliranje procesa je bil uporabljen program z metodo končnih elementov ABAQUS 4.9, instaliran na delovni postaji HP 750. V modelu sta zajeta preoblikovanec in orodje, pri čemer sta upoštevani predpostavki o rotacijski in vzdolžni simetriji procesa. To znatno poenostavi izdelavo modela in zmanjša obseg računanja, saj so osnosimetrični elementi nanizani samo v meridianski polravnini. Glede na predpostavko o vzdolžni simetriji, se model omeji na en sam kvadrant, ki ga omejujeta os rotacije in simetrala, število elementov pa se zmanjša na polovico. Geometrijski parametri orodja in surovca so pri modelu izbrani glede na začetno stanje, posneto pri referenčnem preizku.

Matrica je definirana kot togo telo, medtem ko je za popis lastnosti materiala cevi, ki naj bi bil homogen in izotropen, uporabljen elastoplastičen utrjevalni reološki model, na katerem so v programu ABAQUS tudi sicer zasnovane analize plasto-mehanike. V elastičnem področju je tako material cevi popisan z znanimi vrednostima modula elastičnosti in Poissonovega števila, v plastičnem pa z izmerjeno krivuljo plastičnosti. Torne razmere na stiku med cevjo in matrico so v modelu popisane s Coulombovim zakonom, pri čemer je vrednost tornega koeficiente ocenjena primerjalno, po triboloških pogojih.

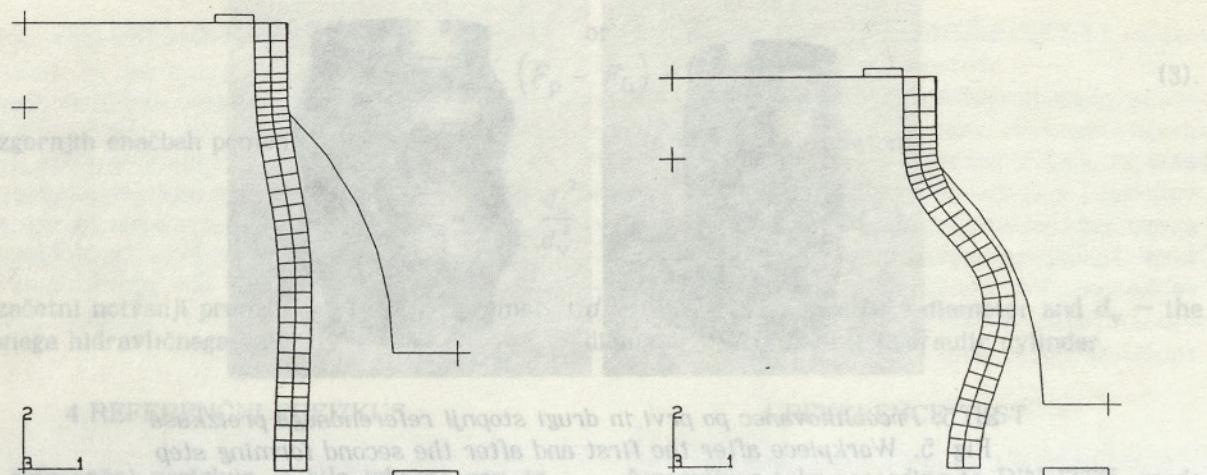
Na podlagi podatkov o poteku obremenitev, izmerjenih pri obeh stopnjah referenčnega preizkusa, sta bili obe zaporedni stopnji računalniško simulirani. Kot neodvisni obremenitvi sta bila izbrana tlak  $p$  in pomik  $\Delta L$ , kar ustreza kombinaciji št. 3 (sl. 2c), kjer pomenita sila  $F_c$  in sprememba notranje prostornine  $\Delta V$  odziv procesa. Zaradi lažje primerjave z referenčnim preizkusom je v računalniškem modelu upoštevana še obremenitev, ki ustreza zadnjemu členu enačbe (3) tako, da se pri računalniškem simuliranju namesto sile  $F_c$  kot rezultat pojavi kar sila blazine  $F_b$ .

## 5 MODELLING AND SIMULATION OF THE PROCESS

A finite element code ABAQUS 4.9 installed on workstation HP 750 was used for modelling and simulation of the process. The model, which takes into account the workpiece and the tooling, is made under the assumption of rotational and longitudinal symmetry of the process. Since the axisymmetric elements are to be defined only in one half-plane, the first assumption considerably simplifies the modelling and reduces the amount of computation. Due to the assumption of longitudinal symmetry the model is further reduced to only one quadrant, limited by the symmetry and rotation axes. Geometrical parameters of the model correspond to those measured on the workpiece and the die at the initial state of the reference test.

The die is defined as a rigid surface, while the properties of the tube, which is assumed to be homogeneous and isotropic, are defined with an elastic-plastic hardening rheological model on which analyses which involve plastic deformations are based in ABAQUS. So the elastic properties of the tube are defined by the known values of the elasticity modulus and the Poisson number, while in the plastic region the measured flow curve is approximated with several linear segments. The Coulomb friction law is used for modelling the conditions within the contact between the tube and the die. The value of the friction coefficient was chosen on the basis of real tribology conditions evaluation.

Considering the measured load data from the reference test, two successive forming steps were simulated. As in the case of load combination No. 3 in figure 2c, the forming pressure  $p$  and die travel  $\Delta L$  were chosen as independant so that the force  $F_c$  and the change of the tube within volume  $\Delta V$  represent the responses of the simulated process. To enable a direct comparison between the simulated results and the measured data, a load which corresponds to the last term in equation (3), is considered in the model, so that instead of force  $F_c$  the cushion force  $F_b$  appears in the model.



Sl. 6. Deformirani mreži, dobljeni pri simuliranju referenčnega preizkusa  
a – po prvi stopnji preoblikovanja, b – po drugi stopnji preoblikovanja

Fig. 6. Deformed net obtained from the simulation of the reference test  
a – after the first step of deformation, b – after the second step of deformation

Na sliki 6 sta prikazani deformirani mreži, dobljeni pri simuliranju prve in druge stopnje referenčnega preizkusa.

#### 6 PRIMERJAVA DEJANSKEGA IN SIMULIRANEGA PROCESA

Glede na že omenjene predpostavke o lastnostih materiala cevi, idealizacijo začetne oblike modela in morebitnih odstopkov izmerjenih vhodnih podatkov modela od dejanskih vrednosti pri referenčnem preizkušu, je mogoče pričakovati tudi določena odstopanja med potekoma simuliranega in dejanskega procesa. Razlike lahko izhajajo tudi iz omejene natančnosti uporabljenih numeričnih metoda, na kar pa je mogoče vplivati zlasti z izbiro vrste elementa in gostote mreže.

Eksperimentalno preverjanje numeričnega modela je bilo zasnovano na primerjavi potekov simulirane in izmerjene sile blazine  $F_b$  ter rezultirajočih oblik meridianskih krivin. Za prvo so bile vrednosti sile blazine iz simuliranega procesa, vnesene v računalniški izris potekov tlaka in sile blazine, ki so bile izmerjene pri referenčnem preizkušu (sl. 7). V obeh diagramih je kot skupni neodvisni parameter uporabljen pomik matrice.

Kakor je razvidno iz diagramov na sliki 7, sta si v obeh stopnjah preoblikovanja simulirana in izmerjena poteka sile blazine dokaj blizu. Razhajanja so nekoliko bolj izrazita le med obremenitvenima korakoma št. 19 in 26 simuliranega procesa. Pri podrobnejši analizi procesa se je izkazalo, da je vzrok za ta razhajanja v prehodni tlačni nestabilnosti, zaradi katere je prišlo pri dejanskem procesu tudi do določenih odstopanj od vzdolžne simetričnosti meridianske krivine (sl. 8).

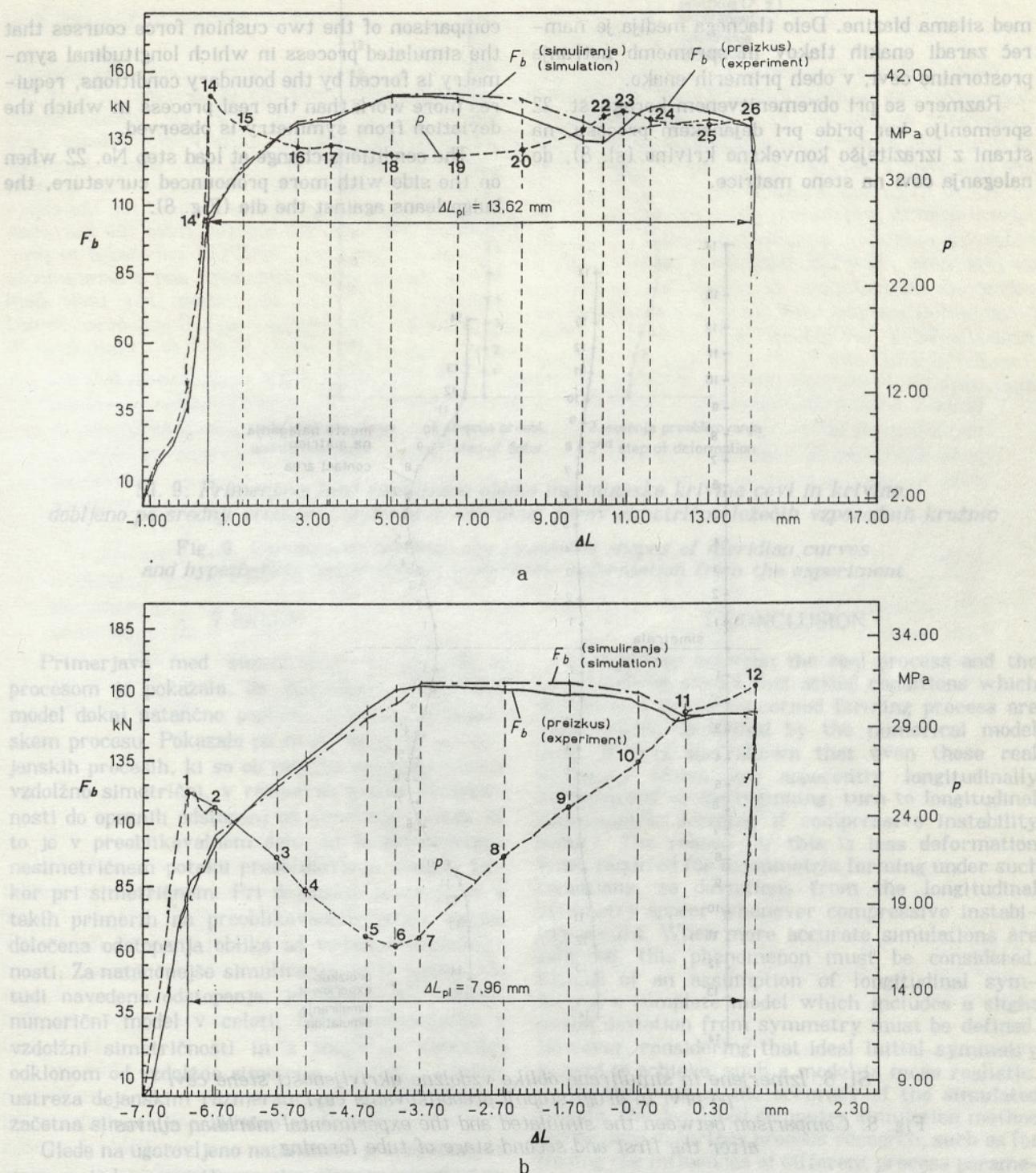
The deformed mesh after the first and the second forming step are shown in figure 6.

#### 6 COMPARISON OF THE RESULTS OF REAL AND SIMULATED PROCESS

With regard to the aforementioned assumptions concerning material properties and idealization of the model geometry, and because of possible measuring errors, some differences between the measured data from the reference test and the simulated process can be expected. Some differences can also result from the limited accuracy of the numerical method used, the latter being dependent on the choice of element type and mesh density.

The experimental verification of the numerical model was based on a comparison between the simulated and measured cushion force  $F_b$  and the resulting shapes of the meridian curvatures. To compare the cushion forces, the values from the simulated process were put into diagrams resulting from automatic on-line measurement during the two forming steps of the reference test (Fig. 7). In both diagrams, a die travel is used as an independent parameter.

As can be seen from the diagrams in figure 7, during both forming steps the cushion force course from the simulated process is very close to that of the reference test. The discrepancies are slightly more pronounced from the load step No. 19 to No. 26 of the simulated process. Detailed analysis of the process showed that this discrepancy resulted from the temporary pressure instability of the real process. This instability also caused some deviations from the longitudinal symmetry of the meridional curvature (Fig. 8).



Sl. 7. Izmerjeni in simulirani potek sile blazine v odvisnosti od pomika matrice in tlaka medija  
a – prva stopnja preoblikovanja cevi, b – druga stopnja preoblikovanja cevi

Fig. 7. Courses of pressure, experimental cushion force and simulated cushion force as functions of die travel  
a – during the first step of forming, b – during the second step of forming

Da ta odstopanja niso naključna, kaže dejstvo, da je skupno preoblikovalno delo med obremenitvenima korakoma št. 19 in 22 v primeru simuliranega procesa, (pri njem je aksialna simetrija vsiljena), večje za razliko, ki izhaja iz razlike

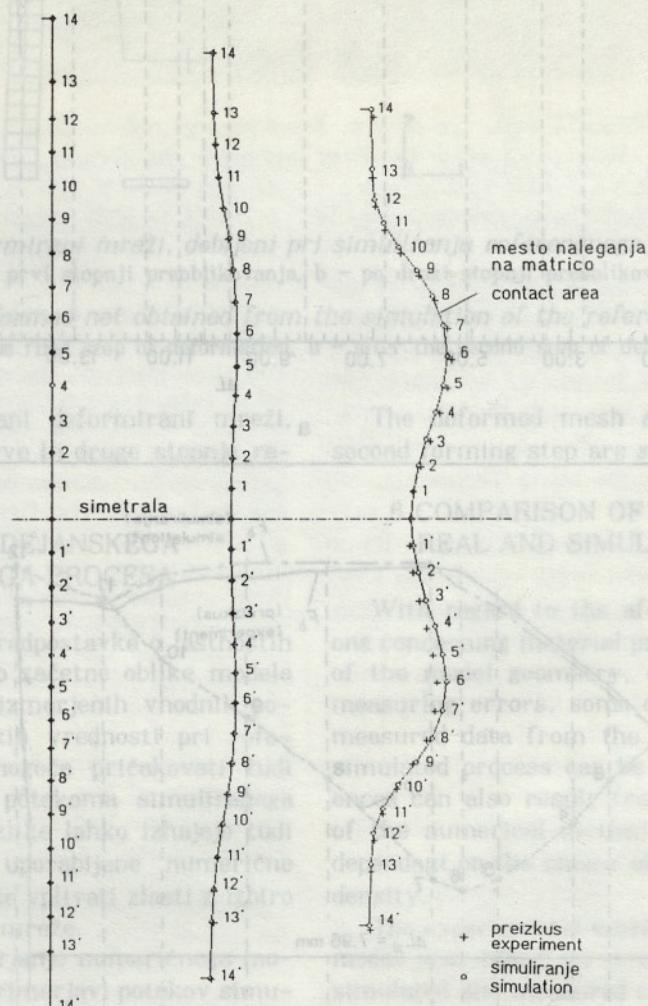
These discrepancies are not coincidental, as is evident from the evaluation of the total work used up in each process from the step No. 19 to No. 22. While the work transmitted by the pressure medium is the same in the simulated process and the real one, it can be seen from the

med silama blazine. Delo tlačnega medija je namreč zaradi enakih tlakov in sprememb notranje prostornine cevi, v obeh primerih enako.

Razmere se pri obremenitvenem koraku št. 22 spremenijo, ker pride pri dejanskem procesu, na strani z izrazitejšo konveksno krivino (sl. 8), do naleganja cevi na steno matrice.

comparison of the two cushion force courses that the simulated process in which longitudinal symmetry is forced by the boundary conditions, requires more work than the real process in which the deviation from symmetry is observed.

The conditions change at load step No. 22 when on the side with more pronounced curvature, the bulge leans against the die (Fig. 8).

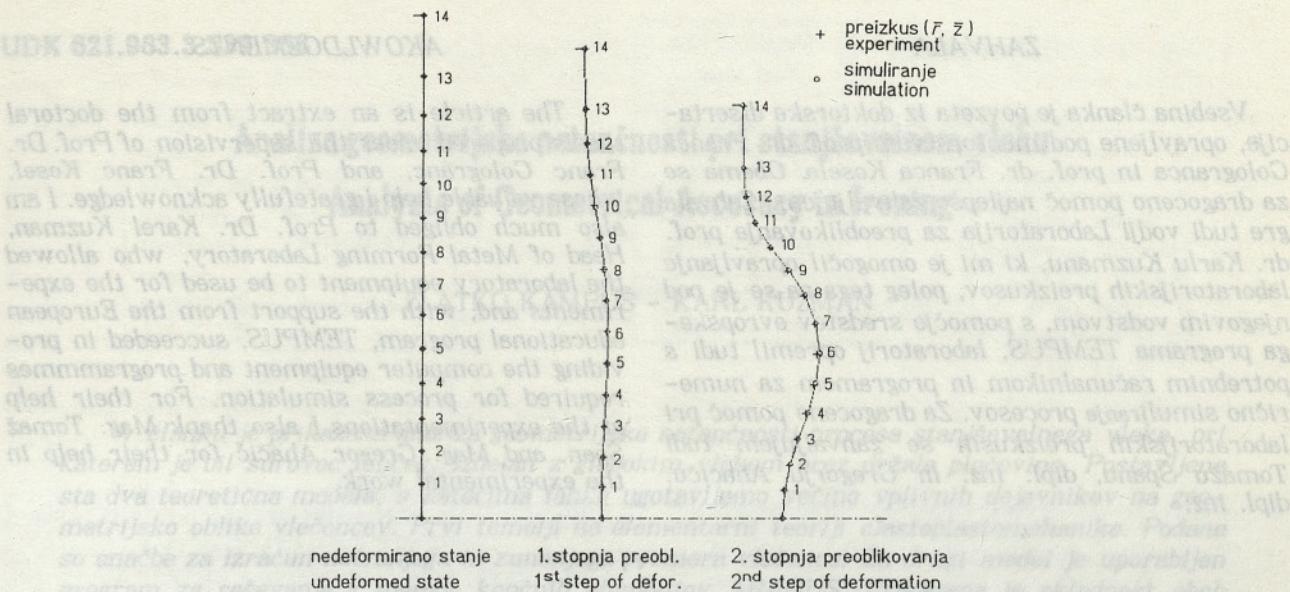


Sl. 8. Izmerjene in simulirane oblike vzdolžne ukrivljenosti stene cevi po prvi in drugi stopnji preoblikovanja cevi

Fig. 8. Comparison between the simulated and the experimental meridional curves after the first and second stage of tube forming

Primerjava meridijskih krivin, opazovanih na zunanji površini cevi pri referenčnem preizkusu oz. simuliranju, pokaže določene razlike zlasti po drugi stopnji. Očitno pa nastajajo te razlike zaradi že omenjenih odstopanj od vzdolžne simetričnosti pri dejanskem procesu. To potrjuje skladnost simuliranih meridijskih krivin s hipotetičnima simetričnima eksperimentalnima krivinama, ki sta bili dobljeni po srednjih vrednostih izmerjenih koordinat ( $\bar{z}$ ,  $\bar{r}$ ), parov simetrično ležečih krožnih raz po prvi in drugi stopnji preoblikovanja (sl. 9).

When comparing the meridional curvature, measured on the outside tube surface, with that from the simulated process, certain differences are noticeable after the second forming step. Obviously, these differences arose from the aforementioned longitudinal asymmetry of the real process. In support of this assumption, very good agreement between the simulated meridional curves and those hypothetical longitudinally symmetrical from the experiment is shown in fig. 9. These curves were obtained by calculating the mean values of coordinates ( $\bar{z}$ ,  $\bar{r}$ ) for each pair of symmetrically lying circular marks after each forming step.



Sl. 9. Primerjava med simulirano obliko meridianske krivine cevi in krivino, dobljeno po srednji vrednosti izmerjenih koordinat parov simetrično ležečih vzorednih krožnic

Fig. 9. Comparison between the simulated shapes of meridian curves and hypothetical longitudinally symmetric deformation from the experiment

## 7 SKLEP

Primerjava med simuliranim in dejanskim procesom je pokazala, da uporabljeni numerični model dokaj natančno popisuje razmere v dejanskem procesu. Pokazalo pa se je, da pride pri dejanskih procesih, ki so ob začetku sicer navidezno vzdolžno simetrični, v razmerah tlačne nestabilnosti do opaznih odstopanj od simetrije. Vzrok za to je v preoblikovalnem delu, ki je pri vzdolžno nesimetričnem poteku preoblikovanja manjše kakor pri simetričnem. Pri dejanskih procesih je v takih primerih na preoblikovancih vedno opaziti določena odstopanja oblike od vzdolžne simetričnosti. Za natančnejše simuliranje, ki bi upoštevalo tudi navedena odstopanja, je zato treba izdelati numerični model v celoti, brez predpostavke o vzdolžni simetričnosti in z majhnim začetnim odklonom od vzdolžne simetrije. To tudi v resnici ustreza dejanskim razmeram, pri katerih idealna začetna simetrija praktično ni dosegljiva.

Glede na ugotovljeno natančnost je mogoče opisano metodo numeričnega simuliranja uporabiti za raziskavo procesa, npr. ugotavljanje vplivov posameznih parametrov na potek in stabilnost procesa ter za ugotavljanje območja začetnih parametrov, pri katerih je proces še stabilen. Slednje je lahko tudi temelj za ugotavljanje območja dosegljivih oblik.

V določenih primerih pa je mogoče na podlagi računalniškega simuliranja optimirati potek obremenitev, povečati dimenzijsko in oblikovno natančnost izdelka, na posameznih mestih preoblikovanca ugotoviti končna stanja plastične utrditve ter določiti potrebno dolžino sručev.

## 7 CONCLUSION

Comparison between the real process and the simulated one shows that actual conditions which are present in the concerned forming process are very exactly described by the numerical model used. It was also shown that even those real processes which are apparently longitudinally symmetrical at the beginning, turn to longitudinal assymmetric forming if compressive instability occurs. The reason for this is less deformation work required for asymmetric forming under such conditions, so deviations from the longitudinal symmetry appear whenever compressive instability occurs. When more accurate simulations are required, this phenomenon must be considered. Instead of an assumption of longitudinal symmetry, a complete model which includes a slight initial deviation from symmetry must be defined. However, considering that ideal initial symmetry is hard to achieve, such a model is more realistic.

On the basis of the accuracy of the simulated results, the described computer simulation method can be used in further process research, such as for finding the influences of different process parameters which affect the process course and stability, as well as for determining the range of initial geometrical parameters in which a stable process can be expected - the latter can also be used as the basis for finding the range of achievable shapes.

In concrete examples, the computer simulation can be used as a basis for process optimisation, which includes the determination of appropriate tube length and load course combination, improvement of the geometrical accuracy of the formed part. In addition, the cumulative plastic deformations and resulting strain hardening can be predicted for any part of the workpiece.

## ZAHVALA

Vsebina članka je povzeta iz doktorske disertacije, opravljene pod mentorstvom prof. dr. Franca Gologranca in prof. dr. Franca Kosela. Obema se za dragoceno pomoč najlepše zahvaljujem. Zahvala gre tudi vodji Laboratorija za preoblikovanje prof. dr. Karlu Kuzmanu, ki mi je omogočil opravljanje laboratorijskih preizkusov, poleg tega pa se je pod njegovim vodstvom, s pomočjo sredstev evropskega programa TEMPUS, laboratorij opremil tudi s potrebnim računalnikom in programom za numerično simuliranje procesov. Za dragoceno pomoč pri laboratorijskih preizkusih se zahvaljujem tudi Tomažu Španu, dipl. inž. in Gregorju Ahačiču, dipl. inž.

## AKOWLDGEMENTS

The article is an extract from the doctoral thesis prepared under the supervision of Prof. Dr. Franc Gologranc, and Prof. Dr. Franc Kosel, whose valuable help I gratefully acknowledge. I am also much obliged to Prof. Dr. Karel Kuzman, Head of Metal Forming Laboratory, who allowed the laboratory equipment to be used for the experiments and, with the support from the European educational program, TEMPUS, succeeded in providing the computer equipment and programmes required for process simulation. For their help at the experimentations I also thank Mag. Tomaz Špan, and Mag. Gregor Ahačič for their help in the experimental work.

## 8 LITERATURE

## 8 REFERENCES

- [1] Ogura, T.—Ueda, T.—Takagi, R.: Über die Anwendung eines hydraulischen Ausbauchverfahrens. Industrie-Anzeiger (88). 1. del: 1966/37, 107–110; 2. del: 1966/48, 137–140.
- [2] Ebbinghaus, A.: Hohleile materialsparend hergestellt. Ind. Anz. 1984/20, 16–17.
- [3] Dohmann, F.—Dudziak, K.: Bau von Werkzeugen und Maschinen zum Innerhochdruckumformen. Bänder Bleche Rohre 1991/8, 19–29.
- [4] Schmoeckel, D.—Engel, B.: Das Hydraulische-Rohr-Innendruck-Umformen eröffnet neue Perspektiven. Umformtechnik, 1991/25, str. 49–53.
- [5] Klaas, F.: Aufweitstauchen von Rohren durch Innerhochdruckumformen. Fortschr. Ber. VDI Reihe 2 1987/142. VDI-Verlag, Düsseldorf.
- [6] Bogojavlenkij, K.N.—Eberlein, L.: Entwicklung und Gestaltung des hydromechanischen Ausbauchens für die industrielle Anwendung. Fertigungstechnik und Betrieb (28) 1978/9, 563–565.
- [7] Lukjanov, V.P.—Kločkov, V.V. in dr.: Hydromechanisches Umformen von Dreiwegstücken mit regelbarem Flüssigkeitsdruck. Kuznečno-štampovočnoe proizvodstvo, (22) 1980/3, 5–7.
- [8] Miyagawa, M.: Flüssigausbauchformverfahren für Rohrabzweigstücke. Blech. Rohre. Profile (30) 1983/1, 32–35.
- [9] Pipan, J.: Proses preoblikovanja cevi z notranjim tlakom in aksialnim pritiskom. Doktorska disertacija. FS, Ljubljana, 1993.

Avtorjev naslov: dr. Janez Pipan, dipl. inž.  
Fakulteta za strojništvo  
Univerze v Ljubljani  
Aškerčeva 6  
61000 Ljubljana

Author's Address: Dr. Janez Pipan, Dipl. Ing.  
Faculty of Mechanical Engineering  
University of Ljubljana  
Aškerčeva 6  
61000 Ljubljana, Slovenia