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Numerične analize preoblikovanja cevi z visokim notranjim tlakom

Numerical Analyses of Tube Hydroforming by High Internal Pressure

Tomaž Pepelnjak

Avtomobilska industrija se zaradi zahtev po povečevanju togosti vozil ob hkratnem zmanjševanju njihove mase srečuje s tehnološkimi problemi izdelave vse bolj zahtevnih preoblikovanih komponent. Oblikovne in mehanske lastnosti preoblikovancev pogosto ne omogočajo več izdelave z običajnimi preoblikovalnimi tehnologijami, kakor so krivljenje, izbočevanje in globoki vlek.

Zaradi zahtevnosti predvsem strukturnih delov avtomobila se vse pogosteje uporablja preoblikovanje cevi z medijem pri visokih notranjih tlakih. Postopek je zaradi velikega števila parametrov zelo zahteven. Preoblikovalni tlaki reda velikosti od nekaj sto do nekaj tisoč barov delujejo v notranjosti cevi in pomenijo omejitev, ki zahteva posebna preoblikovalna orodja in stroje.

V prispevku so predstavljeni parametri preoblikovanja cevi z medijem pri visokih notranjih tlakih, analizirani postopkovni in geometrijski parametri postopka ter izvedene numerične simulacije preoblikovanja dveh tipičnih preoblikovancev – kosa T in kosa Y.

(Ključne besede: preoblikovanje cevi, tlaki visoki, analize končnih elemntov, parametri postopka)

Because of demands for increased vehicle rigidity, along with a simultaneous reduction of vehicle weight, the automotive industry is facing technological problems involving the manufacture of ever more complex formed parts. Often, the shape and mechanical properties of formed parts no longer permit their manufacture using conventional forming technologies, such as bending, stretching and deep drawing.

Due to the complexity of primarily structural vehicle parts, tube hydroforming is increasingly used. However, because of the large number of process parameters, this procedure is very demanding. Forming pressures inside a tube with orders of magnitude of a few hundred to a few thousand bars represent a process limitation that requires special forming tools and machines.

This paper presents the process parameters of tube hydroforming, the analysed process and the geometrical parameters, and the performed numerical simulations for the forming of two typical formed parts –T-parts and Y-parts.

(Keywords: tube hydroforming, finite element analysis, process parameters)

0 UVOD

V sodobni industrijski proizvodnji se pojavlja vedno več razlogov, od katerih je odvisna izdelava tehnološko zelo zahtevnih komponent. Zaradi dragih energetskih virov in surovin iščemo izdelovalne postopke, ki omogočajo izdelavo čim zahtevnejših komponent ob čim manjši porabi energije in najmanjšem odpadku materiala. Zmanjševanje porabe goriva prevoznih sredstev po drugi strani, predvsem v avtomobilski industriji, sili proizvajalce k iskanju optimalnih razmerij med maso vgrajenih komponent in njihovo togostjo. Vse naštete zahteve spodbujajo iskanje novih materialov (npr.

0 INTRODUCTION

In modern industrial manufacture there are ever more reasons for the need to manufacture technologically very complex components. Because of expensive energy sources and raw materials, manufacturing procedures are sought that would enable the manufacture of increasingly complex components with the lowest possible energy consumption and the minimum material waste. On the other hand, the demand to reduce the fuel consumption of transport vehicles forces manufacturers (primarily in the automotive industry) to search for optimum weight-to-rigidity ratia of aluminija, magnezija, večfaznih in mikrolegiranih jekel, kompozitnih materialov ipd.), zasnutkov in tehnologij ([1] in [2]). Sad teh iskanj so sodobne izdelovalne tehnologije in zamisli, kakor so krojeni prirezi, panel pločevine, preoblikovanje z medijem ([3] do [6]). Vpeljevanje novih tehnologij in zamisli poteka tudi v tesni sodelavi z oblikovalci in konstrukterji. Takšna sodelava vodi k vse boljši stroškovni in tehnološki optimizaciji izdelanih proizvodov [7].

Avtomobilska industrija teži tudi k skrajševanju montažnih časov s poenostavljanjem montažnih opravil. Te se v veliki meri skrajšujejo z zmanjševanjem števila vgrajenih komponent, ki so zaradi tega geometrijsko vedno bolj zahtevne [1]. Za izdelavo geometrijsko najzahtevnejših delov, ki se jih z drugimi preoblikovalnimi postopki ne da narediti, so se razvili postopki preoblikovanja z medijem.

Sam postopek preoblikovanja z medijem je v raziskovalnem okolju poznan že dalj časa, saj segajo prve raziskave preoblikovanja tankostenskih cevi z uporabo notranjega tlaka že v šestdeseta in sedemdeseta leta prejšnjega stoletja [8]. Glavne omejitve izredno zahtevnega postopka so takrat predstavljali razpoložljivi hidravlični stroji, preoblikovalni stroji ter pomanjkanje ustrezne računalniško opreme za napovedovanje poteka preoblikovalnega postopka. S skokovitim razvojem strojne opreme in programov za računalniško podprte simulacije preoblikovalnih postopkov (analize MKE) se je bliskovito razširila uporaba preoblikovanja cevastih preoblikovancev z visokimi notranjimi tlaki medija – t.i. “tube hydroforming”. Postopek se je najprej uporabljal pri proizvodnji geometrijsko zahtevnih izpušnih sistemov. V zadnjih desetih letih ta postopek vedno več uporabljajo tudi pri izdelavi nosilnih delov karoserije, nosil motorja, oseh in gredeh ter varnostnih karoserijskih komponentah kakor so nosila vetrobranskih stekel, A, B in C nosila, blažila, okrovi sedežev itn. Tudi na Fakulteti za strojništvo v Ljubljani so potekale raziskave postopkov sorodnih preoblikovanju cevi z visokimi notranjimi tlaki s ciljem izdelati kroglaste okrove iz cevastih surovcev ([9] in [10]).

Najpomembnejše prednosti postopka preoblikovanja z visokimi notranjimi tlaki lahko strnemo v naslednjih točkah:
- Preoblikovati se da zelo zahtevne geometrijske oblike cevastih izdelkov, ki se jih z drugimi preoblikovalnimi postopki ne da narediti.
- Zaradi zahtevne geometrijske oblike lahko več sestavnih delov sklopa nadomestimo z enim samim izdelkom, kar poenostavlja montažo in s tem izboljšuje izdelovalne tolerance.
- Trdnost izdelkov in porazdelitev debelin sta zaradi »mehkega« delovanja sil med preoblikovanjem enakomernejša kakor pri drugih postopkih.
- Tanjšanje materialov med preoblikovanjem je

installed components. All of these demands encourage manufacturers to search for new materials (e.g. aluminium, magnesium, multiphase and microalloyed steels, composite materials etc.), concepts and technologies ([1] and [2]). These endeavours have resulted in modern manufacturing technologies and concepts, such as tailored blanks, sandwich steel, hydroforming, etc. ([3] to [6]). New technologies and concepts are also implemented in close cooperation with designers and mechanical engineers, which leads to ever better optimisation of the manufacturing technology and product costs [7].

There is also a tendency in the automotive industry to shorten assembly times by simplifying assembly operations. This is achieved mainly by reducing the number of components, which, as a result, need to have increasingly complex geometrical shapes [1]. Hydroforming procedures have been developed specifically for the manufacture of the geometrically most demanding parts, which cannot be produced using other forming processes.

The hydroforming process has been known for a while in research circles. The first research in the forming of thin-walled tubes using inner pressure date back to the 1960s and 1970s [8]. The main limitations of this extremely complex process were hydraulic aggregates and the forming machines that were available at that time, as well as a lack of appropriate computer equipment for predicting the course of the forming process. With the rapid developments in machine equipment and software for computer-aided simulations of the forming process (FE analyses), the use of tube hydroforming has spread very quickly. This process was first used in the manufacture of geometrically demanding exhaust systems. Over the last ten years, this procedure has also been increasingly used in the manufacture of space-frame components, engine cradles, axles and shafts, and body and safety parts, such as windshield headers, A, B and C pillars, shock absorbers, seat frames, etc. Research in other processes similar to tube hydroforming has also been conducted at the Faculty of Mechanical Engineering, Ljubljana, with the goal of manufacturing spherical housings from tubular formed parts ([9] and [10]).

The most important advantages of the hydroforming process can be summarised as follows:
- Very complex geometries of tubular formed parts can be achieved, which are not attainable with other forming processes.
- Due to complex geometry, several components of an assembly can be replaced with a single formed part, thus simplifying the assembly and improving manufacturing tolerances.
- “The softer” action of the forces during forming yields more uniform strength and thickness distribution than other equivalent processes.
- The thinning of materials during forming is smaller

manjše kakor pri drugih postopkih.
- Masa komponent je zaradi enakomernejše porazdelitve debelin manjša v primerjavi z izdelki, narejenimi z drugimi tehnologijami.
- Delež elastičnega izravnavanja je manjši kakor pri drugih postopkih, zato lahko izdelujemo preoblikovance z boljšimi izdelovalnimi tolerancami.
- Površina izdelkov je zelo gladka.

Pomanjkljivost postopka preoblikovanja z visokimi notranjimi tlaki je predvsem zelo draga oprema in zahtevno krmiljenje parametrov postopka. Visoki procesni tlaki v orodjih, ki se gibljejo od nekaj sto do nekaj tisoč barov, terjajo posebno konstrukcijo orodij, veliko trdnost orodnih materialov in ustrezne varnostne ukrepe. Zaradi naštetih zahtev so orodja za preoblikovanje z medijem dražja od orodij za druge preoblikovalne postopke.

than in other equivalent processes.
- Because of a more uniform thickness distribution, component weight is lower than with other equivalent technologies.
- Springback is also lower than in other processes, therefore formed parts can be produced using better manufacturing tolerances.
- The surfaces of these products are very smooth.

The shortcomings of tube hydroforming are mainly very expensive equipment and demanding process-parameter control. High process pressures in the die, ranging from a few hundred to a few thousand bars, require a special tool structure, a high strength of tool material and the appropriate safety elements. Because of this, hydroforming tools are more expensive than those for equivalent forming processes.

1 ZNAČILNOSTI POSTOPKA

Postopek preoblikovanja z medijem z visokim notranjim tlakom popišemo s sklopom vplivnih parametrov, ki jih delimo v štiri skupine:
- parametri postopka (vzdolžna sila, zapiralna sila, notranji tlak, pomiki itn.),
- omejitve postopka (gubanje, izbočenje, izbruh, trenje),
- parametri surovca (dolžina, premer, debelina, material, oblika),
- orodje (oblika, kakovost površine, trdota).

Vplivni parametri prve skupine se med preoblikovanjem spreminjajo, med postopkom jih moramo nadzorovati in krmiliti. Omejitve postopka, npr. gubanje, izbočenje in izbruh, so povezani z geometrijsko obliko in materialom preoblikovanca. Osnovne enačbe pojava omenjenih kritičnih napak na preoblikovancu temeljijo na izbočenju cevi, prekoračitvi natezne trdnosti materiala in čezmernem nakrčevanju, ki pripelje do pojava gubanja preoblikovanca ([11] in [12]):

1 PROCESS CHARACTERISTICS

The hydroforming process is described with a set of influential parameters, which are divided into four groups:
- Process parameters (axial force, closure force, inner pressure, feedings, etc.),
- Process limitations (wrinkling, buckling, bursting, friction),
- Formed-part parameters (length, diameter, thickness, material, shape),
- Tools (shape, surface quality, hardness).

The influential parameters from the first group vary during forming and should be regulated and controlled during the process. Process limitations such as wrinkling, buckling and bursting are related to geometry and workpiece material. The basic equations for the appearance of the above-mentioned critical defects on the formed parts are the result of tube buckling, exceeding of the material's tensile strength and excessive upsetting, which leads to the appearance of wrinkling ([11] and [12]):

Izbruh : prekoračitev natezne trdnosti:

Bursting: exceeding of tensile strength:

$$p_n = \frac{2\, s_0\, R_m}{d_0 - s_0} \qquad (1).$$

Gubanje: prevelik vzdolžni pomik cevi:

Wrinkling: excessive axial tube feedings:

$$\sigma_a = \frac{2\, E_T\, s_0}{1,65\, d_0} \qquad (2).$$

Lokalizacija: prekoračitev izbočilne odpornosti cevi:

Localisation: exceeding the tube-buckling resistance:

$$\varepsilon = \varepsilon_e \qquad (3),$$

kjer so p_n notranji tlak, R_m natezna trdnost materiala, s_0 in d_0 debelina in premer cevi, σ_a vzdolžna napetost med preoblikovanjem, E_T tangentni modul materiala in ε_e primerjalna specifična deformacija cevi.

V zadnjih letih se bazične raziskave preoblikovanja z medijem usmerjajo vedno bolj v iskanje ustreznih maziv ter v analize vplivov različnih

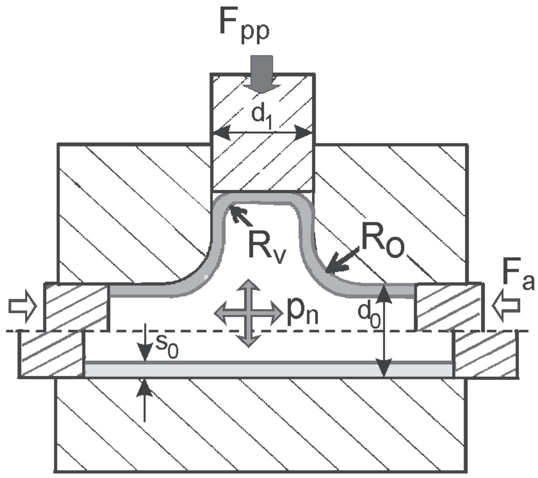
where p_n is the inner pressure, R_m is the tensile strength of the material, s_0 and d_0 are the tube thickness and diameter, respectively, σ_a is the axial stress during forming, E_T is the tangent modulus and ε_e is the equivalent specific tube deformation.

Over the past few years, basic research in hydroforming has focused on the search for koeficientov trenja na potek postopka preoblikovanja z visokimi notranjimi tlaki. Poseben poudarek je na oblikovanju izdelka, porazdelitvi debelin izdelka in napakah, ki se pojavljajo zaradi neustreznega trenja [13].

Geometrijski parametri surovca in preoblikovanca so pomembni pri določevanju izdelovalnih tehnoloških mej postopka in v veliki meri vplivajo na kakovost izdelave s postopkom preoblikovanja z visokim notranjim tlakom. Osnovne geometrijske parametre prikazuje slika 1 na primeru tipičnega preoblikovanca – kosa T [12].

appropriate lubricants and analyses of the influence of different coefficients of friction on the course of the hydroforming process. Special emphasis is placed on product design, thickness distribution and the defects resulting from inappropriate friction [13].

The geometric parameters of the preform and the formed part are important for determing the manufacturing technological process limits and have a large effect on the quality of hydroforming-based manufacture. The basic geometric parameters are shown in Figure 1, for an example of a typical formed part – T-part [12].

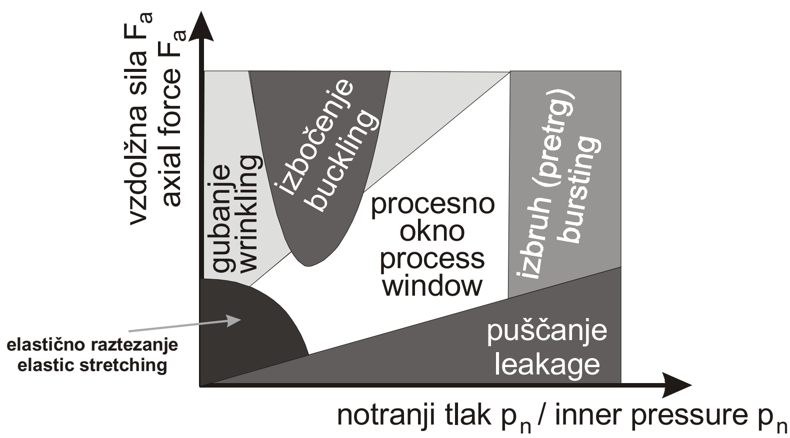


d_0	začetni premer cevi / *initial tube diameter*
s_0	začetna debelina cevi / *initial tube thickness*
d_1	premer oblike T / *diameter of the T-feature*
R_o	polmer orodja / *die radius*
R_v	polmer zaokrožitve izbočitve oblike T / *radius of the T-feature*
p_n	notranji tlak / *inner pressure*
F_a	vzdolžna sila pestičev / *axial punch force*
F_{pp}	sila protipestiča / *counterpunch force*

Sl. 1. *Geometrijski parametri preoblikovanca [12]*
Fig. 1. *Geometric parameters of the formed part [12]*

Najpomembnejša parametra postopka, ki ju med postopkom spreminjamo, sta gib orodja oziroma vzdolžna sila, s katero delujemo na preoblikovanec ter notranji tlak. Oba parametra postopka moramo za optimalno preoblikovanje cevastega preoblikovanca med postopkom nadzorovano spreminjati znotraj meja tehnološkega okna uspešnega preoblikovanja. Slednje je opredeljeno s kritičnimi napakami preoblikovanca in ga najlepše prikažemo v diagramu

The most important process parameters, which are varied during the process, are the punch stroke or axial force on the formed part, and the inner pressure. For optimum forming of tubular parts, both process parameters must be varied in a controlled manner during the process, within the limits of the technological window for successful forming. The latter is defined by critical defects on the formed part and is best shown by a diagram of the variation of the axial



Sl. 2. *Diagram odvisnosti vzdolžne sile od notranjega tlaka [14]*
Fig. 2. *Diagram of the variation of axial force with inner pressure [14]*

odvisnosti vzdolžne sile od notranjega tlaka med preoblikovanjem (sl. 2). V primeru prenizkih vzdolžnih sil sistem ne tesni, pri premajhnih vzdolžnih silah in tlakih pa ne presežemo meje plastičnosti preoblikovanega materiala. Preveliki notranji tlaki povzročijo izbruh, prevelike vzdolžne sile ob ustreznih notranjih tlakih pa pojave gubanja in izbočenja cevi.

Poznavanje vseh naštetih vplivnih parametrov smo analizirali na preoblikovanju kosa T in kosa Y s poudarkom na vplivih koeficienta trenja in vzdolžnih pomikov pestičev na oblikovanje končnega izdelka.

2 NUMERIČNE (MKE) ANALIZE PREOBLIKOVANJA CEVI Z VISOKIM NOTRANJIM TLAKOM

2.1 Analiza preoblikovanja kosa T

Preoblikovanje kosa T je ena glavnih oblik preoblikovanja cevi z medijem. Na izbočenje in oblikovanje oblike T v največji meri vplivajo geometrijska oblika cevi in orodja, vzdolžne sile pestičev, časovno spreminjanje notranjega tlaka ter trenje med preoblikovancem in orodjem. Na primeru preoblikovanja cevi iz jekla 1.0333.6 smo v računalniško podprtem okolju analizirali vpliv koeficientov trenja na oblikovanje kosa T. Analize so bile izvedene z numeričnim reševanjem problema z metodo končnih elementov (MKE) in izvedene z računalniškim programom Abaqus Explicit verzija 6.3 [15]. Model orodja in preoblikovanca (cevi) za analize MKE in upoštevane materialne lastnosti cevi so prikazani na sliki 3. Na sliki so zaradi boljše preglednosti izpuščeni vzdolžni pestiči ter protipestič. Enoosna simetrija omogoča uporabo polovičnega modela celotnega sistema orodje - preoblikovanec.

Pri izbiri časovnega poteka delovanja notranjega tlaka smo izbrali profil s hitrim povečevanjem tlaka do vrednosti p_{n1}, ki zagotavlja pričetek plastičnega deformiranja materiala ter

force with inner pressure during forming – Figure 2. If the axial forces are too low, the system is not fluid-tight, whereas at insufficient axial forces and pressures the yield strength of the formed material is not exceeded. Excessive inner pressures cause bursting, whereas excessive axial forces with appropriate inner pressures cause tube wrinkling and buckling.

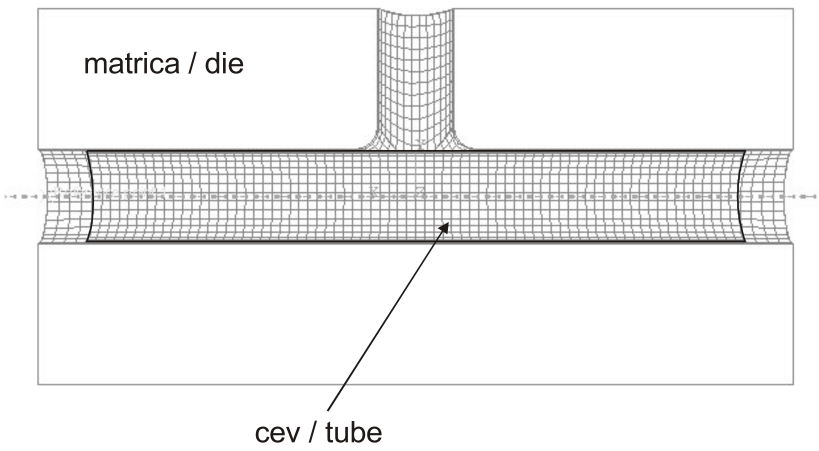
All of the stated influential parameters were analysed on the forming of T-parts and Y-parts, with the emphasis on the influence of the coefficient of friction and the axial punch feedings on the forming of the final products.

2 NUMERICAL FINITE-ELEMENT ANALYSES OF TUBE HYDROFORMING

2.1 Analysis of T-part forming

The forming of a T-part is one of the basic types of tube hydroforming. The factors affecting the forming of T-parts are the tube and die geometry, the axial punch forces, the time variation of the inner pressure, and the friction between the formed part and the die. The influence of the coefficient of friction on T-part forming was analysed in a computer-aided environment for the case of tube forming made of 1.0333.6 steel. The analyses were performed numerically using the finite-element method (FEM) and the software Abaqus Explicit Ver. 6.3 [15]. The model of the tool and the formed part (tube) for FE analyses, and the material properties of the tube, are shown in Figure 3. In this figure the axial punches and the counterpunch are omitted for better clarity. Uniaxial symmetry enabled the use of a half-model for the tool/formed-part system.

For the time variation of the action of inner pressures, a curve with quick increases of pressure up to the value of p_{n1} was selected to ensure the initiation of plastic deformation of the material and



Lastnost Property	Vrednost Value
E	210 GPa
ν	0,3
ρ	7800 kg/m^3
R_p	215 MPa
R_m	350 MPa
C	537 MPa
n	0,227
r	1

Sl. 3. *Model MKE orodja in cevi za izdelavo kosa T*
Fig. 3. *FE model of tool and tube for manufacturing T-parts*

linearno povečevanje tlaka do vrednosti p_{n2} ob koncu preoblikovanja. Vrednost tlaka p_{n2} smo izbrali tako, da še ne pride do izbruha zaradi lokalnega stanjanja preoblikovanca.

Analizo vpliva koeficienta trenja na oblikovanje izbočitve T smo izvedli najprej brez protipestiča pri dveh vrednostih vzdolžnih pomikov l_a obeh koncev cevi: $l_a = 1,5*d_0$ (30 mm) ter $l_a = 2*d_0$ (40 mm). Izbrane velikosti vzdolžnih pomikov so velike v primerjavi s sorodnimi raziskavami v svetu [16]. Z velikimi vzdolžnimi pomiki smo skušali doseči čim manjše tanjšanje debelin stene preoblikovanca med samim postopkom. Pri vrednotenju vpliva trenja na geometrijsko obliko kosa T sta bili vpeljani brezrazsežno razmerje izbočitve T TH_r:

linear increases of the pressure up to the value of p_{n2} at the end of the forming. The values of pressure p_{n2} were selected such that bursting does not take place because of the formed part's local contraction.

Analyses of the influence of the coefficient of friction on T-part forming were initially performed without a counterpunch for two values of the axial displacement l_a of the two tube ends: $l_a = 1.5*d_0$ (30 mm) and $l_a = 2*d_0$ (40 mm). The selected values of the axial displacement are high compared to similar international studies [16]. Large axial displacements were used in an attempt to achieve minimum reduction of the formed-part wall thicknesses during the forming process. When evaluating the influence of friction on T-part geometry, we introduced the dimensionless T-feature ratio, TH_r:

$$TH_r = \frac{H}{d_1} \tag{4}$$

in relativna višina izbočitve izb_r, podana kot razmerje:

and the relative feature height izb_r, given as the following ratio

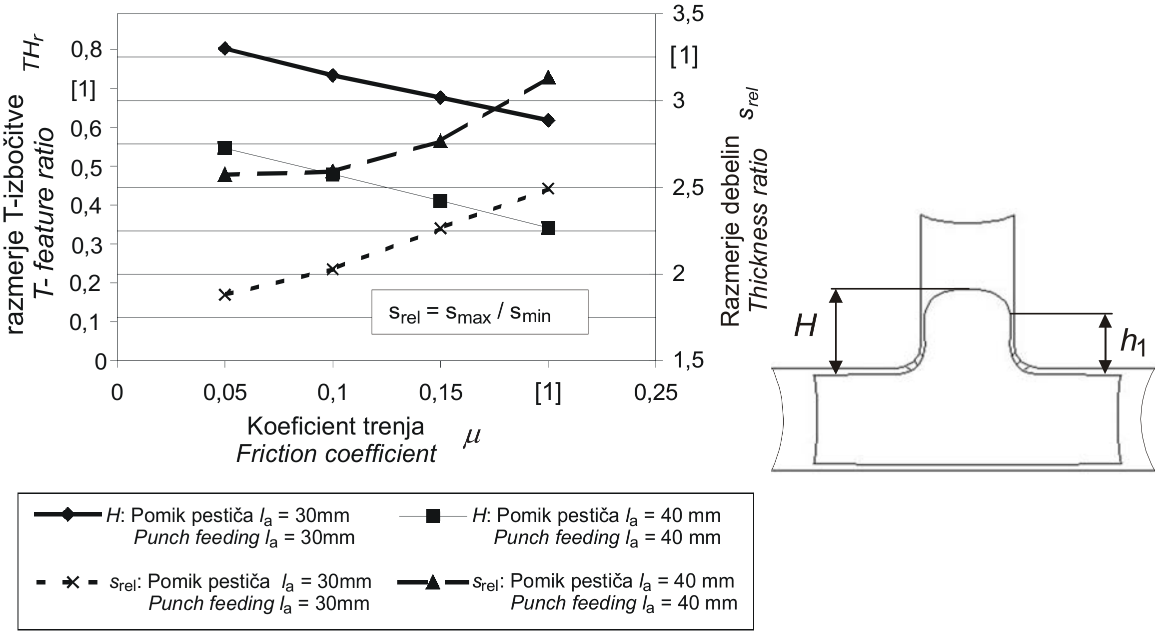
$$izb_r = \frac{H - h_1}{d_1} \quad (5),$$

kjer so H višina izbočenega dela izdelka T, h_1 višina cevasto izbočenega dela izdelka T in d_1 premer izbočenega dela izdelka.

Surovec ima izmere ϕ 20x160 mm z debelino stene 1 mm. Rezultati vrednotenja izbočitve kosa T so prikazani na sliki 4. S slike je razvidno, da sta višina izbočitve, podana z razmerjem TH_r, ter koeficient trenja μ med orodjem in preoblikovancem pri izbranih preoblikovalnih parametrih linearno odvisna. Analiza izbočitve kosa T z razmerjem izb_r je pokazala, da

where H is the T-feature's height, h_1 is the height of the T-feature's tubular portion and d_1 is the T-feature's diameter.

The tube's dimensions were ϕ 20x160 mm and the wall thickness was 1 mm. The results of the T-feature evaluation are shown in Figure 4. This figure shows that the feature's height, given as the TH_r ratio, and the coefficient of friction μ between the die and the formed part at the selected forming parameters are in a linear relationship. The analysis



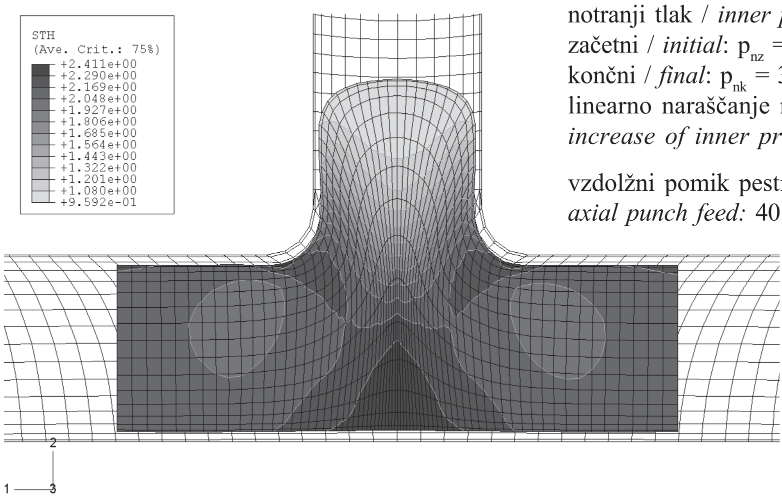
Sl. 4. *Vpliv koeficenta trenja na izbočitev (leva lestvica) in razmerje debelin kosa T (desna lestvica)*
Fig. 4. *The influence of the coefficient of friction on the T-feature's dimensions (left scale) and T part's thickness ratio (right scale)*

višina ukrivljenega dela izbočitve ni odvisna niti od koeficienta trenja niti od velikosti vzdolžnega pomika pestičev. S spreminjanjem vrednosti koeficientov trenja med orodjem in preoblikovancem ob nespremenjenih preostalih parametrih postopka se spreminja le višina izbočenega dela kosa T (*TH*$_r$*)* ter razmerje debelin najdebelejšega in najtanjšega dela izdelka (sl. 4).

Porazdelitev debelin preoblikovanega kosa T, izdelanega brez delovanja protipestiča, je prikazana na sliki 5. Izbrani parametri postopka z velikimi pomiki vzdolžnih pestičev zagotavljajo najmanjše tanjšanje kosa T. Po drugi strani se hkrati pojavlja neobičajna odebelitev koncev cevi, okolice polmera R_0 in stene nasproti izbočene oblike T.

of the T-feature with the *izb*$_r$ ratio showed that the height of the curved part of the feature does not depend on the coefficient of friction or the magnitude of the axial punch feedings. When the magnitude of the coefficient of friction is varied with other process parameters unchanged, only the T-feature's height (*TH*$_r$*)* and the ratio of thicknesses of the thickest to the thinnest portion vary - Figure 4.

The thickness distribution of a T-part formed without the use of a counterpunch is shown in Figure 5. Selected process parameters with large displacements of axial punches have ensured minimal thinning of the T-part. On the other hand the uncommon thickening at the tube ends, around the die radius R_o and on the wall opposite the T-feature took place.



notranji tlak / *inner pressure* :
začetni / *initial*: p_{nz} = 25 MPa
končni / *final*: p_{nk} = 38 MPa
linearno naraščanje notranjega tlaka / *linear increase of inner pressure*

vzdolžni pomik pestičev
axial punch feed: 40 mm

Sl. 5. *Porazdelitev debelin kosa T, izdelanega brez protipestiča*
Fig. 5. *Thickness distribution of a T-part produced without the use of a counterpunch*

Izdelava kosov T v industriji zahteva uporabo protipestičev, ki zmanjšajo ločno izbočeni del kosa T $H_1 = H - h_1$ (sl. 4). V ta namen med preoblikovanjem kosa T na prosto preoblikovani del cevi delujemo s silo protipestiča, ki zmanjšuje izbočenost končnega priključka T. Slika 6 prikazuje izdelavo kosa T z uporabo protipestiča in silo njegovega delovanja. Izbrani parametri postopka zagotavljajo najmanjše tanjšanje izdelka , ki doseže le 3% na vrhu izbočene oblike T.

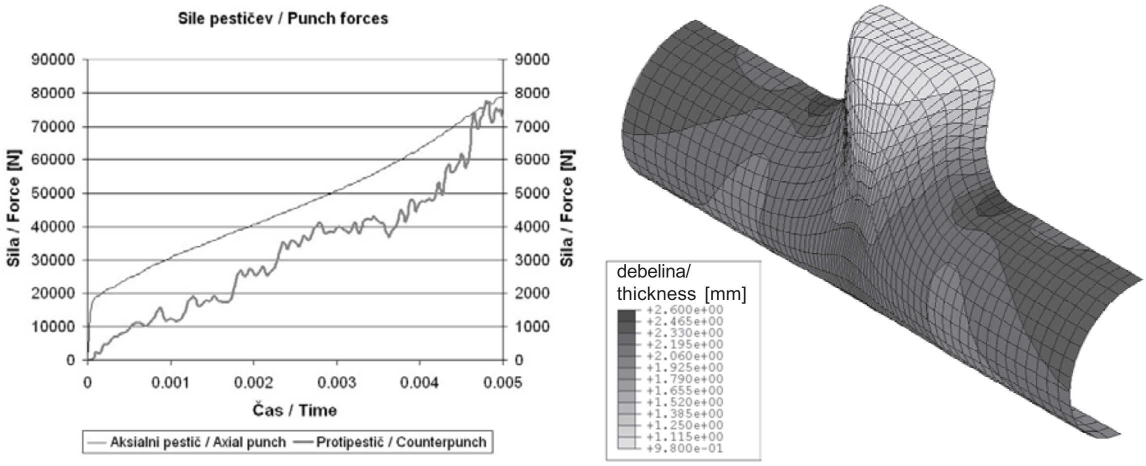
The industrial manufacture of T-parts requires the use of counterpunches, which reduce the arched portion of the T-feature $H_1 = H - h_1$ (Figure 4). For this purpose, a force is applied on the free-formed portion of the tube using a counterpunch during the T-part's forming. This force reduces the arched portion of the T-feature on the final product. Figure 6 shows the production of a T-part using a counterpunch and its force. The selected process parameters ensure minimum thinning of the part – only 3% on the top of the T-feature.

2.2 Analiza preoblikovanja kosa Y

V izpušnih sistemih, ki so eno pomembnejših področij preoblikovanja z visokimi notranjimi tlaki, se pogosto pojavljajo zahteve po izdelavi razcepov in priključkov, ki se na glavno cev ne spajajo pod pravim kotom. Tako imenovani kos Y je za izdelavo precej zahtevnejši kakor v prejšnjem poglavju obravnavani kos T. Geometrijska oblika kosa zahteva nesimetrične pomike vzdolžnih pestičev med preoblikovanjem. Vpliv velikosti pomika posameznega konca preoblikovanca se kaže v obliki priključka kosa Y. V

2.2 Analysis of Y-part forming

The manufacture of exhaust systems, one of the most important applications of hydroforming, frequently involves the production of manifolds and connectors that are not attached to the main tube at an angle of 90 degrees. The production of Y-parts is much more difficult than that of the T-parts described in the previous section. This part's geometry requires asymmetric feedings of axial punches during forming. The influence of the magnitude of displacement of the formed part's ends is reflected in the shape of the Y-part



notranji tlak / *inner pressure* :
začetni / *initial*: p_{nz} = 25 MPa
končni / *final*: p_{nk} = 38 MPa
linearno naraščanje notranjega tlaka / *linear increase of inner pressure*

vzdolžni pomik pestičev
axial feed of punches: 40 mm

Sl. 6. *Potek preoblikovalnih sil in porazdelitev debelin modela MKE kosa T, izdelanega z uporabo protipestiča*
Fig. 6. *Forming forces vs. time and thickness distribution of a FE model of a T-part made using a counterpunch*

delu smo analizirali vplive različnih velikosti pomikov robov cevi kosa Y. Zaradi primerljivosti dobljenih rezultatov z že znanimi [17] smo izbrali kos Y s 60 stopinjskim priključnim delom.

Podobno kakor pri analizi kosa T smo izvedli numerične simulacije preoblikovanja kosa Y z notranjim tlakom, izračunanim po enačbi 1 v poglavju 2.1. Izbrani material je imel enake materialne karakteristike kakor v poglavju 2.1. Surovec ima dimenzije ϕ 20x160 mm iz jekla 1.0333.6 z debelino stene 1 mm. Model orodja in surovca za izdelavo kosa Y je prikazan na sliki 7. Zaradi večjih pomikov desnega dela preoblikovanca je izbrani razcep Y v orodju na tretjini dolžine surovca. Enoosna simetrija preoblikovanca omogoča tudi v tem primeru analize s polovičnim modelom MKE. V primeru simulacije kosa Y se je pokazalo, da ne moremo več zadostiti pogoju najmanjšega tanjšanja stene cevi. Kot kriterij uspešnega preoblikovanja smo zato izbrali največje dovoljeno tanjšanje cevi, ki je opredeljeno z enačbo:

connector. This paper analyses the influences of various displacements of the Y-part's tube ends. In order to enable comparisons of the obtained results with published results [17], a Y-part with a 60-degree connector was selected.

As with the analysis of the T-part, numerical simulations of Y-part forming were performed with an inner pressure calculated using Equation 1, section 3.1. The selected material had the same characteristics as stated in section 3.1. The preform's dimensions were ϕ 20x160 mm and it was made of 1.0333.6 steel with a wall thickness of 1 mm. The model of the die and tube for the production of the Y-part is shown in Figure 7. Because of greater displacements of the right portion of the formed part, the selected Y-feature in the die is located at one third of the tube's length. In this case as well, the formed part's uniaxial symmetry enabled FE half-model-based analyses. The simulation of the Y-part showed that the condition of minimum tube wall thinning could no longer be met. As a criterion of successful forming, the maximum permissible tube thinning was therefore selected, which is defined with the equation:

$$s_1 = s_0 * e^{-n} \qquad (6).$$

Izbrane so bile različne kombinacije pomikov pestičev, pri čemer smo za pomik levega pestiča izbrali vrednosti $l_{a1} = d_o$ (20 mm) in $l_{a1} = 1,5*d_o$ (30 mm). Pomike desnega pestiča smo spreminjali v razponu vrednosti od $l_{a2} = 1,5*l_{a1}$ (30 mm) do $l_{a2} = 3,5*l_{a1}$ (80 mm) s korakom po $0,25*l_{a1}$. Časovni profil notranjega tlaka medija med preoblikovanjem je bil pri vseh

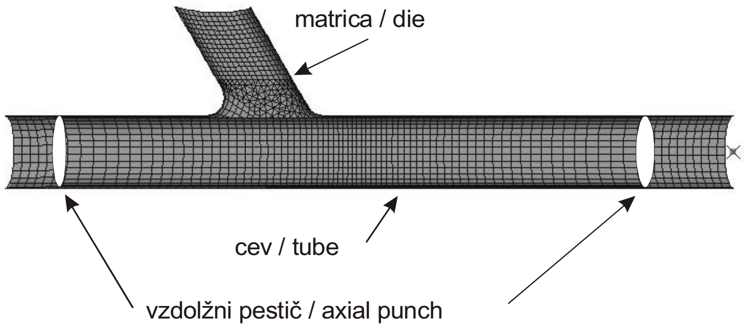
Various combinations of punch feedings were used. For left punch feedings we used the values of $l_{a1} = d_o$ (20 mm) and $l_{a1} = 1.5*d_o$ (30 mm). Right punch feedings were varied over the interval between $l_{a2} = 1.5*l_{a1}$ (30 mm) and $l_{a2} = 3.5*l_{a1}$ (70 mm), with an increment of $0.25*l_{a1}$. The variation of the fluid's inner pressure with time during forming was identical analizah preoblikovanja enak. V prvih 10% celotnega časa smo izbrali hitro naraščanje notranjega tlaka v cevi do vrednosti, ki povzroči plastifikacijo cevi. V nadaljevanju smo do konca preoblikovanja tlak linearno povečevali do mejne vrednosti, podane z enačbo [17]:

in all the analyses of forming. During the first 10% of the total time, the inner pressure was increased quickly up to the tube's yield strength. Thereafter, the pressure was increased in a linear fashion until the end of forming, up to a limit given by equation [17]:

$$p_n = \frac{4\, s_0\, R_m}{d_0 - s_0} \qquad (7).$$

Koeficent trenja ima nespremenljivo vrednost μ=0,05.

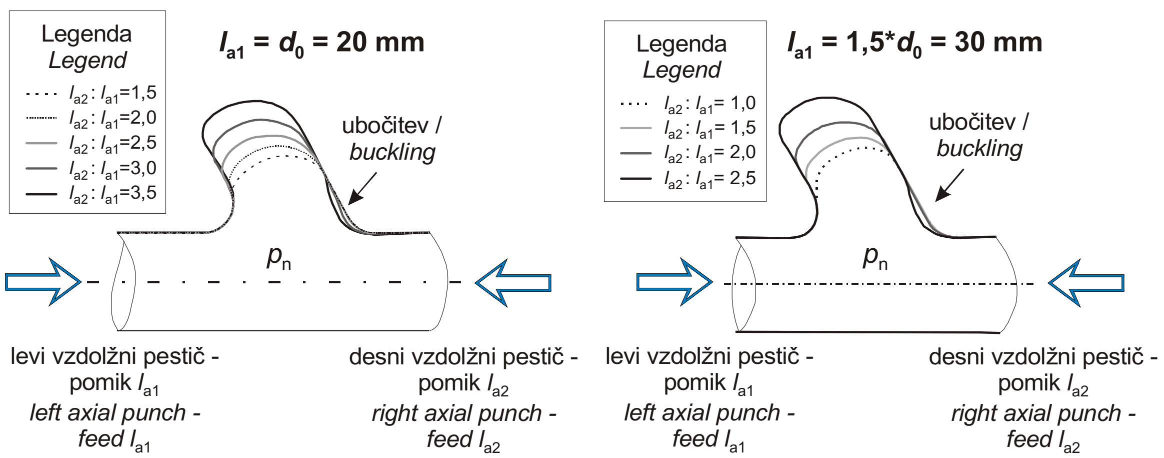
The coefficient of friction had a constant value of μ=0.05.



Sl. 7. *Model MKE orodja in cevi za izdelavo kosa Y*
Fig. 7. *FE model of tool and tube for the manufacture of a Y-part*

V simulacijah preoblikovanja smo analizirali višino kraka Y, njegovo obliko in debelino. Kriterija mejnega uspešnega preoblikovanja sta bila dovoljeno tanjšanje materiala (enačba 6) in pojav ubočitve preoblikovanca na prehodu cevi v krak Y. Ubočitev se pojavi ob prevelikem pomiku desnega vzdolžnega pestiča. Analize so pokazale, da se v primeru levega pomika pestiča za $l_{a1} = d_o$ pojavi guba na kraku Y pri trikratni velikosti pomika desnega pestiča ($l_{a2}/l_{a1} = 3$), medtem ko se pri večjem pomiku levega pestiča ($l_{a1} = 1{,}5*d_o$) ta guba pojavi že pri vrednosti $l_2/l_1 = 2{,}25$.

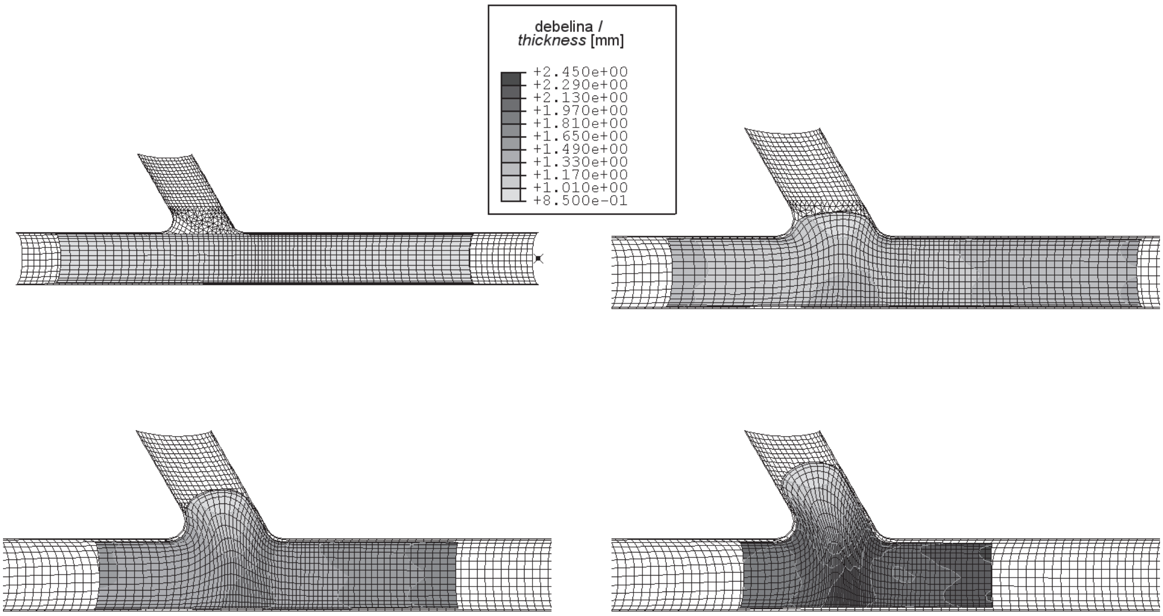
During simulations of forming, the Y-feature's height was analysed, along with its shape and thickness. The used limits for successful forming were the permissible material thinning (Equation 6) and the appearance of buckling on the transition from the tube to the Y-feature. Buckling appears at excessive right axial punch feedings. Analyses showed that for left punch feedings of $l_{a1} = d_o$, a wrinkle appears on the Y-feature at three times the value of right punch feeding ($l_{a2}/l_{a1} = 3$), whereas during greater left punch feedings ($l_{a1} = 1.5*d_o$) this wrinkle appears already at a value of $l_{a2}/l_{a1} = 2.25$.



Sl. 8. *Oblika kraka Y pri različnih pomikih vzdolžnih pestičev*
Fig. 8. *Y-feature at different axial punch feedings*

Oblikovanje kraka Y v odvisnosti od pomikov pestičev je prikazano na sliki 8 – pomik levega pestiča $l_{a1} = d_o$ (levo) in $l_{a1} = 1,5*d_o$ (desno). Potek preoblikovanja in porazdelitev debelin največjega uspešno izdelanega kosa Y s pomiki vzdolžnih pestičev l_{a1} = 30 mm in l_{a2} = 60 mm sta prikazana na sliki 9.

The forming of Y-feature vs. punch feedings is shown in Figure 8 – left punch feedings $l_{a1} = d_o$ (left) and $l_{a1} = 1,5*d_o$ (right). The course of forming and the thickness distribution for the largest successfully produced Y-part with punch feedings l_{a1} = 30 mm and l_{a2} = 60 mm are presented in Figure 9.



Sl. 9. *Porazdelitev debelin največjega uspešno preoblikovanega kosa Y*
Fig. 9. *Thickness distribution of the largest successfully formed Y-part*

V industrijskem okolju izdelava preoblikovanca sestoji iz več tehnoloških faz, od katerih smo simulirali le najpomembnejšo fazo – preoblikovanje z visokim notranjim tlakom. Pred to fazo se v notranjost cevi dovaja še tlačni medij in povečuje tlak do delovnega tlaka medija, po samem preoblikovanju pa sledi še faza kalibracije. Ta faza se uporablja samo pri preoblikovanju s protipestiči, v njej se preoblikovancu s povečanim kalibracijskim tlakom da končno obliko izdelka.

Analizo preoblikovanja kosa Y s protipestičem smo izvedli za kombinaciji vzdolžnih pomikov pestičev, pri katerih smo dobili največji še uspešno izdelani krak Y izdelka. To sta kombinaciji pomikov l_{a1} = 20 mm : l_{a2} = 55 mm in l_{a1} = 30 mm : l_{a2} = 60 mm. Končno obliko izdelka, ki naleže na protipestič pri 32% pomika vzdolžnih pestičev, prikazuje slika 10. Na sliki je prikazana tudi oblika izdelka po fazi kalibracije, v kateri smo povečali notranji tlak medija za 50% končne vrednosti tlaka med preoblikovanjem.

In industrial environments, the production of hydroformed parts consists of several technological phases, of which only the most important one, the forming procedure, was simulated. Prior to this phase, a pressure medium is fed to the tube's interior and it increases the pressure up to the working pressure. Forming is followed by the calibration phase, which is only used in forming with counterpunches; increased calibration pressure is applied in order to give the formed part its final shape.

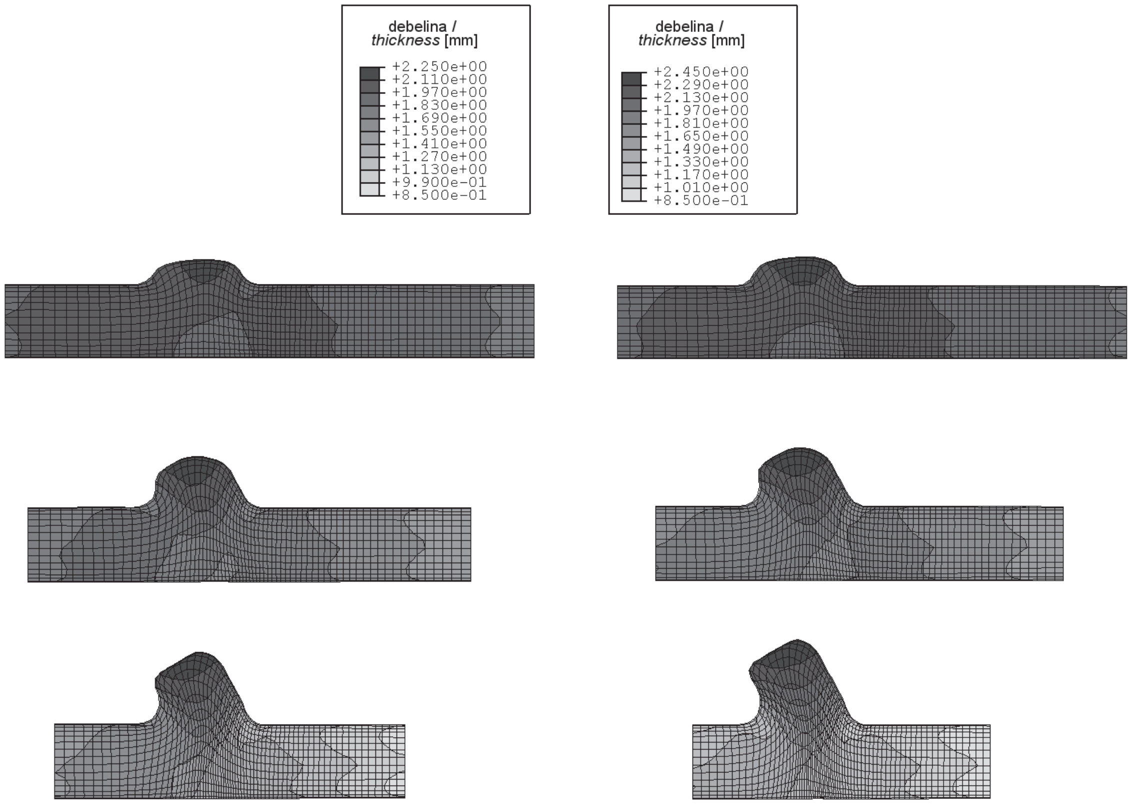
The analysis of Y-part forming using a counterpunch was performed for the combinations of axial punch feedings at which the largest still successfully formed Y- feature was obtained. These were feeding combinations of l_{a1} = 20 mm : l_{a2} = 55 mm and l_{a1} = 30 mm : l_{a2} = 60 mm. The final product portion which comes into contact with the counterpunch at 32% axial punch feeding is shown in Figure 10. This figure also shows the formed part's shape after the calibration phase, in which the medium's inner pressure was increased by 50% of the final pressure value during forming.

3 SKLEPI

Preoblikovanje z visokimi notranjimi tlaki se vedno bolj uveljavlja v avtomobilski industriji pri izdelavi izpušnih sistemov ter nosilnih in strukturnih

3 CONCLUSIONS

Hydroforming is increasingly used in the automotive industry for the manufacture of exhaust systems, and load-bearing and structural



Sl. 10. *Izdelava kosa Y z uporabo protipestiča na 1/3 (zgoraj), 2/3 (v sredini) preoblikovanja in po kalibraciji (spodaj) - pomiki l_{a1} = 20 mm : l_{a2} = 55 mm (levo) in l_{a1} = 30 mm : l_{a2} = 60 mm (desno)*
Fig. 10. *Manufacture of a Y-part using a counterpunch at 1/3 (top), 2/3 (middle) of forming time and after forming (bottom) – punch feedings l_{a1} = 20 mm : l_{a2} = 55 mm (left) in l_{a1} = 30 mm : l_{a2} = 60 mm (right)*

delov avtomobila. Sama tehnologija preoblikovanja z visokimi notranjimi tlaki je zaradi velikega števila časovno spremenljivih parametrov postopka zelo zahtevna. Veliko število vplivnih parametrov je odvisno tudi od geometrijske oblike surovca in izdelka ter uporabljanega materiala.

Zaradi velikega števila vplivnih veličin postopke preoblikovanja z visokimi notranjimi tlaki načrtujemo v navideznem računalniško podprtem okolju, ki omogoča variacije posameznih parametrov postopka in iskanje optimalnih tehnoloških rešitev. Vplivnost koeficienta trenja in vzdolžnih pomikov pestičev sta analizirana na preoblikovanju kosa T in kosa Y. V obeh primerih smo notranjost cevi obremenjevali z notranjim tlakom, ki smo mu med preoblikovanjem linearno spreminjali vrednost. Velikost tlaka smo spreminjali od vrednosti, potrebne za plastično deformacijo cevi na začetku, do tlaka, ki še ne povzroči lokalizacije in izbruha na koncu preoblikovanja. Analize preoblikovanja kosa T brez protipestiča so pokazale linearno povezanost koeficienta trenja in izbočenosti preoblikovanca. Preoblikovanec se zaradi tlačnih vzdolžnih obremenitev ob večjih pomikih pestičev v največji meri odebeli pri koncih cevi, v okolici polmera orodja

components. Because of the large number of process parameters that vary with time, hydroforming technology is very demanding. A large number of influential parameters also depend on the geometry of the preform and formed part and the material used.

Because of a large number of influential parameters, hydroforming procedures are planned in a virtual environment that enables the variation of individual process parameters and searching for optimum technological solutions. The effects of the coefficient of friction and axial punch feedings are analysed on the forming of T-parts and Y-parts. In both cases, the inside of the tube was subjected to an inner pressure, the value of which was varied during forming in a linear manner. The magnitude of the pressure was varied from the value required for initial plastic tube deformation to a value just before localisation and bursting at the end of forming. An analysis of T-part forming without a counterpunch showed a linear relationship between the coefficient of friction and the formed part's feature. Because of the axial pressure loads, thickening of the formed part's wall is most pronounced at large punch feedings on tube ends, around the die radius R_o and on the

R_o in na steni preoblikovanca nasproti izbočene oblike T. Do najmanjšega tanjšanja prihaja le na najbolj izbočenem delu preoblikovanca. Analize so pokazale, da se vrednosti tanjšanja v izbranih preoblikovalnih razmerah pri jeklu 1.0333.6 gibljejo vedno pod 7% začetne debeline stene.

Preoblikovanje izdelka Y, ki se uporablja v veliki meri pri izdelavi priključkov in razvodov izpušnih sistemov, smo analizirali glede na različne vzdolžne pomike cevi med postopkom. Zaradi oblike Y ne moremo uporabljati simetričnih pomikov cevi. Glede na izmere cevi, končno geometrijsko obliko kosa Y ter dovoljeno tanjšanje materiala se izbira velikost vzdolžnih pomikov. Pri izbranih velikostih pomikov levega pestiča v velikosti $l_{a1} = d_o$ in $l_{a1} = 1,5*d_o$ sta za uspešno preoblikovanje cevi največja dovoljena pomika desnega pestiča $l_{a2} = 2,75 * l_{a1}$ v prvem in $l_{a2} = 2 * l_{a1}$ v drugem primeru.

Predstavljene analize preoblikovanja kosa T in kosa Y bomo v nadaljevanju raziskovalnega dela razširili z geometrijsko zahtevnejšimi uporabami ter vrednotenji vplivov različnih kombinacij pogojev vzdolžnih sil in notranjih tlakov na oblikovanje končnega izdelka.

wall opposite the T-feature. Minimum thinning takes place only on the most prominent portion of the formed part. Analyses have shown that the values of thinning during the selected forming conditions for steel 1.0333.6 always range below 7% of the initial wall thickness.

The forming of Y-parts, which is largely used in the production of manifolds and connectors for exhaust systems, was analysed in terms of the different axial tube displacements during the procedure. Because of the Y-feature, symmetric tube displacements could not be used. The magnitude of axial feedings is selected based on tube dimensions, the final Y-feature geometry and permissible material thinning. At the selected left punch feedings of $l_{a1} = d_o$ and $l_{a1} = 1.5*d_o$, the maximum permissible right punch feedings for successful tube forming are $l_{a2} = 2.75 * l_{a1}$ in the first case and $l_{a2} = 2 * l_{a1}$ in the second case.

In the continuation of our research, the presented analyses of the forming of T-parts and Y-parts will be expanded with geometrically more complex applications and evaluations of the influence of different combinations of axial forces and inner pressures on the forming of final products.

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