

FINITE ELEMENT APPROACH TO ANALYSIS OF AXISYMMETRIC REVERSE DRAWING PROCESS

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The intention of this research is to make analyze of deep drawing Cr-Ni stainless steel process. The research is related to forces that appear in machine tool during the process and also to material stress and its behaviour. The results are taken from two sources and their comparison is made. The first source of results are experiments made on hydraulic press, and the other source are results obtained by creation of finite element model (FEM) and process simulation on MSC Marc Mentat program package. The measurements are made in cases of different reduction coefficient and different tool material. Comparison that is given is related to punch and pressure plate forces, and the state of material stress for each reduction coefficient is observed too. Datasheets and force diagrams present the results, and material stress can be seen on figures that are result of the simulation.

Key words: *FEM, reverse drawing, material stresses, cracking possibility, MSC Marc program package*

Pristup metodom konačnih elemenata analizi procesa osnosimetričnog protusmjernog dubokog vučenja. Namjera provedenog istraživanja jest načiniti analizu procesa dubokog vučenja Cr-Ni nehrđajućeg čelika. Istraživanje se odnosi na sile koje se javljaju u alatu tijekom procesa te također na pojavu naprezanja u materijalu i ponašanje dotičnog naprezanja. Rezultati su uzeti iz dva izvora i načinjena je njihova usporedba. Prvi izvor su rezultati eksperimenata izvedenih na hidrauličnoj preši, a drugi izvor čine rezultati dobiveni kreiranjem modela metodom konačnih elemenata (MKE) i simulacija procesa pomoću programskog paketa MSC Marc Mentat. Eksperimentalna mjerenja načinjena su za različite koeficijente redukcije. Dana je usporedba rezultata koji se odnose na silu u žigu alata i pritisak na rondelu, a također je promatrano stanje naprezanja u materijalu za svaki koeficijent redukcije. Rezultati su prikazani u obliku tablica i dijagrama, a naprezanja u materijalu prikazana su na slikama dobivenim kao izlazni podaci simulacije procesa metodom konačnih elemenata.

Ključne riječi: *MKE, protusmjerno vučenje, naprezanja u materijalu, mogućnost pucanja, MSC Marc Mentat programski paket*

INTRODUCTION

Deep drawing of a metal sheet is a standard technique that is widely used in order to fabricate thousands of sheet metal structures per day in many industries, e.g. automotive, aerospace, beverage industry etc.

One of the biggest challenges in deep drawing metal forming is to achieve the final product by very few draws. Thus, it makes possible to reduce time and expenses of production. Reverse drawing is an operation developed from the standard deep drawing process. Its purpose is to convert two draws of the standard process into one operation. In this way one can have greater d_1/d_2 ratio without stopping the process and also without taking down the working piece. As all of these actions take time to be

done, the time and of course the expenses are automatically saved.

Actual position of reverse drawing process in the world is a production of aluminium and copper and their alloy products. Deep drawing of Cr-Ni stainless steel presents an actual problem because of a great hardening of these alloys during metal forming processes [1].

However, reliable FE models and simulations for describing the process are of a great value in reducing much of the tool tryout work. In this way, improvements of the process are made before making expensive tools needed for experimentation. In that way experiments are needed just to verify the simulation.

THE PROBLEM ESTABLISHMENT

As we are trying to reduce the number of needed draws, in each draw the reduction coefficient is becoming

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smaller than before, sometimes even smaller then recommended one.

In sheet-forming processes however, several type of failures could occur, such as rupturing, necking, wrinkling and too large spring back that are undesirable. In this case they are result of the existence of inappropriate forces and material stresses during reverse drawing Cr-Ni stainless steel process. The main task is to avoid these failures by careful analyzing of its all-possible causes.

The scheme of the reverse drawing operation shows the way it works and its main components.

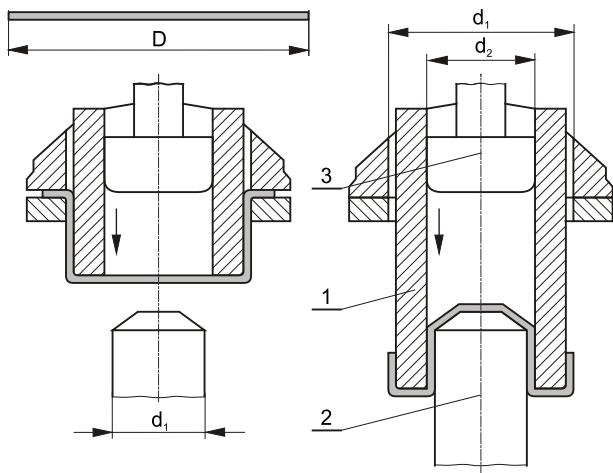


Figure 1. The scheme of the reverse drawing operation: 1-hollow punch, 2-second draw punch, 3-hydraulic knockout bar [2]

Slika 1. Shema procesa protusmjernog dubokog vučenja: 1-xxx, 2-xxx, 3-xxx [2]

Looking the scheme, we can assume the way this process works: in a first draw punch is moving into a die in order to plastically deform a blank sheet of metal into a desired shape as it does in usual deep drawing process, and achieves d_1 diameter. After first draw is stopped, the second draw punch is starting its motion in the opposite direction. It is pushing the bottom of the working piece into hollow punch, which now becomes a die for the second draw, giving it new diameter d_2 . The working piece gets its final shape and is pushed out by hydraulic knockout bar.

In a deep drawing process, change of working pieces shape is made by simultaneous activity of tensile stress on the outside surface of the piece, compressive stress on the inside surface of the piece (result is diameter reduction), and by bending the piece around bottom corners of the punch (change of direction). Bending increases sum-total of all stresses.

In a first draw, diameter reduction, from blank sheet diameter to first draw diameter, can be relatively large because the bending participation is usually small. On the opposite, in other draws, the bending participation is greater and allowed coefficient of shape changing must be reduced. The differ-

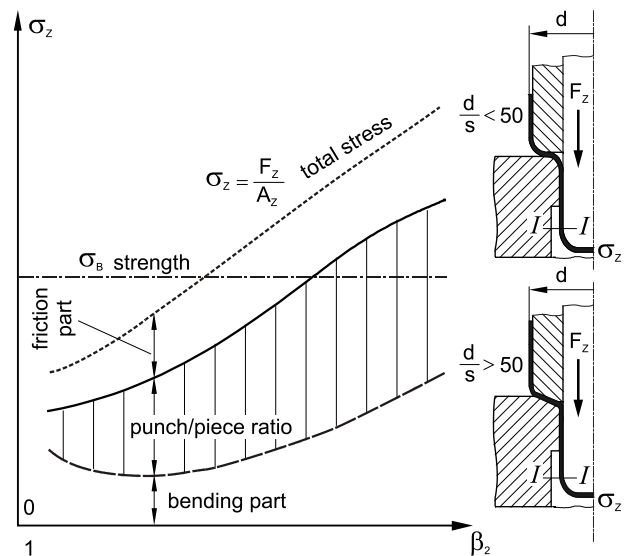


Figure 2. Stresses that appear in standard deep drawing operation [3]

Slika 2. Naprezanja u standardnom procesu dubokog vučenja [3]

ence between bending of standard second draw and second draw in reverse drawing is in number of direction changing that occur in it. In standard deep drawing second draw exists triple bending (1. bending in direction of motion, 2. bending in the opposite direction, 3. straightening), and in reverse drawing second draw it happens four times (1. bending in direction of motion, 2. straightening, 3. bending in direction of motion, 4. straightening). Because of that difference, there is also a difference in stresses that appear in material. Very good description of stress difference is $\beta_2 - \sigma_z$ (drawing ratio - total stress) diagrams. Beside them are schemes of the operations that show direction changes of material.

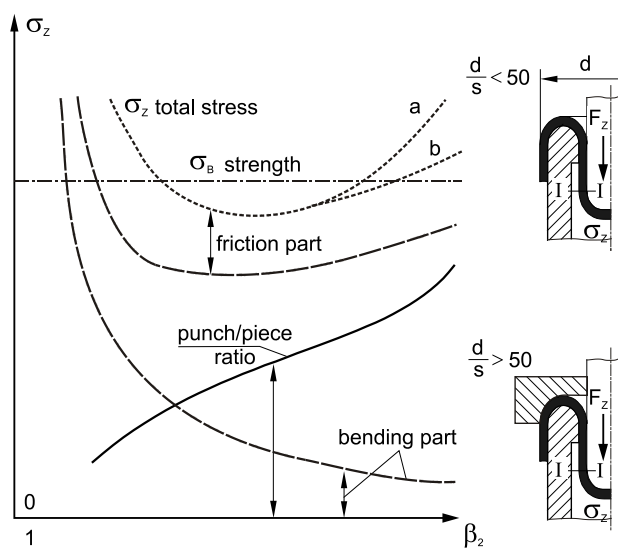


Figure 3. Stresses that appear in reverse drawing operation [3]

Slika 3. Naprezanja u procesu protusmjernog dubokog vučenja [3]

It is obvious that because of greater stresses, second draw in reverse drawing, and is very much alike to produce some of the failures. That is why stresses should be estimated and watched very carefully.

Main parameters that need to be carefully calculated and considered are:

- reduction coefficients in each draw, related - needed number of draws;
- tool dimensions and shapes;
- tool forces;
- material stresses and its hardness in each draw.

EXPERIMENTATION

The intention of experiments that were carried out was to analyze a pot producing from a 1 mm thick blank sheet of a diameter D 145 mm to a final diameter d_2 53 mm through two draws. After first draw, calculated and achieved diameter was d_1 80 mm. Analyzed material was Cr-Ni stainless steel. Because of very few known data about this material's behaviour in reverse drawing processes, some authors suggest heating on temperature of 150 - 200 °C [3]. This experimentation was referred to carrying out a process in a cold state. Experiments were made on double acting hydraulic press. The double action refers to the clamping mechanism moving independently of the punch mechanism. This allows for the boundaries of the sheet blank to be clamped while the punch pushes the sheet into the die cavity. The ability to independently control both the clamp and the punch affords the opportunity for various modifications of the experimental procedure. It needs to be accented that reverse drawing processes are recommended to be drawn at triple acting presses [4], but because such equipment is not accessible, the experiment was performed at double acting press.

A few questions got their answers by making modifications in experimental parameters:

1. How much reduction coefficient of the first draw can be reduced?
2. How does the punch force act if we change reduction coefficient (by changing blank sheet diameter D , we change reduction coefficient of the first draw)?
3. How does the punch force change in a second draw in relation to the change of punch force and reduction coefficient in a first draw?

Material properties

Material that was processed is X 5 Cr Ni 18 10 with: 0,037 % C; 0,343 % Si; 1,019 % Mn; 0,031 % P; 0,0015 % S; 18,155 % Cr; 8,927 % Ni; 0,032 % N. But, as it is well known, the same chemical composition can have different mechanical properties. This is a consequence of different ways of sheet rolling (different numbers of reduction), and

also different heating treatment. Mechanical properties are given in Table 1. The most important mechanical property in this case is ductility, expressed with A80 : 57,3 - 60,2 %.

Table 1. **Mechanical properties**
Tablica 1. **Mehanička svojstva**

	$R_{p0,2} /$	$R_{p1} /$	$R_m /$	A80 /	HRB
	N/mm ²	N/mm ²	N/mm ²	%	
X 5 CrNi 18 10	268	296	603	57,3	76,5
	-	-	-	-	-
	272	302	612	60,2	77,0

Sheet surface was highly polished with foil rolled on both sides that was used as a lubricant.

Experiment and the results

In metal forming technology standard experiment models are applied. Usually those are factor analyses with one or more factors. In this particular case, one-factor experiment method is used. It can be observed that in such experiments result dependence on just one factor is a fiction. It is possible to find several more factors that have influence on final result. Such idealisation in complex cases can be justified in certain circumstances:

- if factors that are not expressed are maintained in constant level,
- if their influence is negligible,
- if their influence is accidental and is possible to use methods of mathematical statistics to separate their influence from controlled factor in calculated experimental error.

In this case condition of constant level is satisfied.

A choice about the number of experiments is made according literature [5]. Probability of 50 % with probability level of 0,90, demands at least 7 measurements for each factor level.

The reduction coefficient is defined by the following expression [6]:

$$m = \frac{D_1}{D_0} \quad (1)$$

where:

- m - reduction coefficient,
- D_1 - pot diameter after specific draw,
- D_0 - pot diameter or a blank sheet diameter before specific draw.

It is well known that after any cold plastic deformation, material strength grows up and ductility decreases. There-

fore, reduction coefficient must be bigger in each draw, and is specifically defined for each draw and also for each material. In a first draw, its minimum is about 0,60 and in a second draw its minimum is about 0,80. Because this numerical coefficient grows up, it means that deformation level becomes smaller which is acceptable in relation to a smaller material ductility. When reduction coefficient is changed,

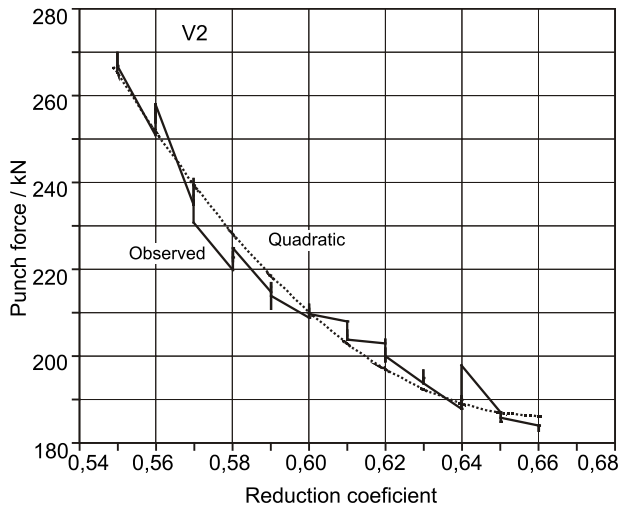


Figure 4. Diagram punch force/reduction coefficient in a first draw
Slika 4. Dijagram sila žiga/koeffcijent redukcije u prvoj fazi

blank holder force is constant, punch force is changing too. The smaller reduction coefficient is, the punch force grows up. Also, the stress hardening grows up with smaller reduction coefficient, and because of greater plastic deformation, material strength grows up too and ductility decreases. No special lubricant was used, but instead of it a polymer foil was applied. Punch speed was 0,020 m/s.

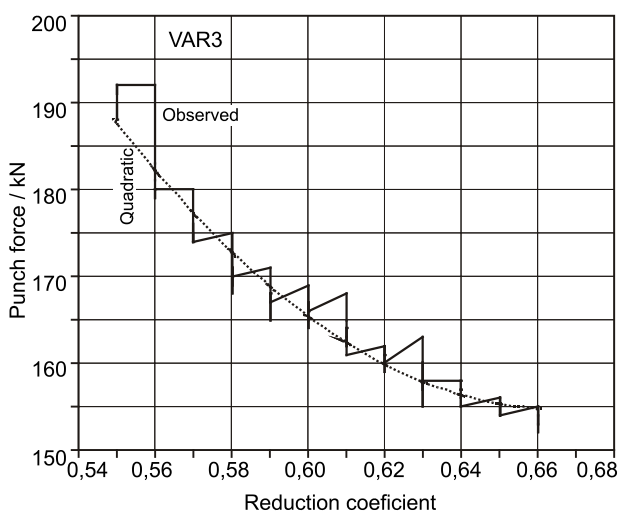


Figure 5. Diagram punch force/reduction coefficient in a second draw
Slika 5. Dijagram sila žiga/koeffcijent redukcije u drugoj fazi

In the experiment, reduction coefficient was changed in a first draw from 0,55 to 0,66. With smaller reduction coefficient built-in material stresses were too large, so, in the second draw cracking took place. By changing reduction coefficient, punch force was changing from 270 kN to 185 kN. According to plan of experiment 84 measurements are made. Analyse is carried out using program package SPSS for statistical analyses.

Third question that need an answer is related to the second draw. It is very interesting to observe how changes of parameters in a first draw influence on the change of parameters in a second draw. Specifically: how does the punch force change in a second draw in relation to the change of punch force and reduction coefficient in a first draw? Reduction coefficient in the second draw is constant and amounted 0,68. Punch force in a second draw related to reduction coefficient in a first draw is shown in Figure 5.

Cracking avoidance

As it is well known, mentioned sort of stainless steel is a material with extreme hardening in metal forming processes. That is why those processes demand great control of all process parameters and avoidance of any unnecessary imposed material stress. In this particular case problem can be created with large blankholder force. It is expressed in case of the smallest reduction coefficient in a first draw ($m = 0,55$) when all stresses reach their maximal value. All residual stresses are remaining in second draw and cause cracking. To avoid it blankholder force in a first draw has to be held in smallest level that provides regular drawing – 20 kN. In greater reduction coefficients sum total of all stresses is becoming smaller and naturally, risk of cracking is smaller too [4].

Change of sheet thickness is a phenomenon that needs to be observed and mentioned in context of cracking possibility. In the experiment that was carried out sheet thickness was measured on final product for each reduction coefficient. The most important change occurred at critical points (beginning of bottom round). This change varied from 0,1 to 0,3 mm related to change of reduction coefficient in a first draw. It is important to notice that change of 0,3 mm is even 30 % of sheet thickness and occurs when reduction coefficient reaches 0,55.

RESULTS OF THE SIMULATION

The numerical analysis was preformed using MSC Marc Mentat elasto-plastic program commercial package. In the presented deep drawing problem, the full Newton-Raphson iterative procedure is chosen to solve the iteration process and nonlinear equations of motion. This method has quadratic convergence properties and the stiffness matrix is reassembled in each iteration. Convergence

can be slowed down by some approximations, but these computational problems are of a less importance when iterative solvers are used. Since material elements rotate during deep drawing process, large displacement, finite

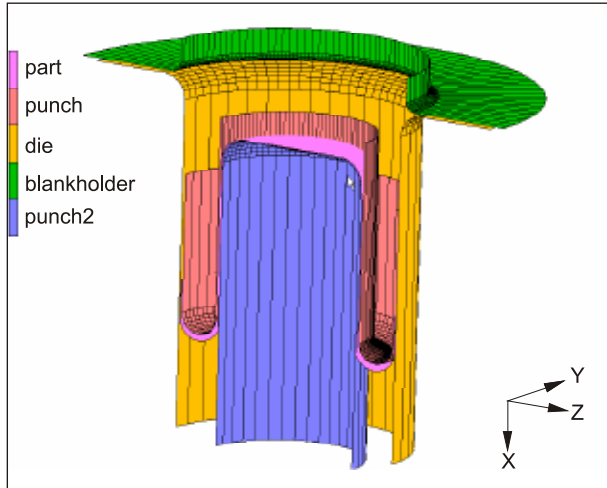


Figure 6. 3D view of working piece and tool
Slika 6. 3D prikaz radnog komada i alata

strain plasticity and updated Lagrange procedure need to be adopted in calculation. In the Lagrangian approach, the element stiffness is assembled in the current configuration of the element, and the stress and strain output is given with respect to the coordinate system in the updated configuration of the element [7].

The stiffness is formed using four point Gaussian integration. Because of large displacements request, an additional contribution needed to be made to the stiffness matrix. By default, the analysis program uses the

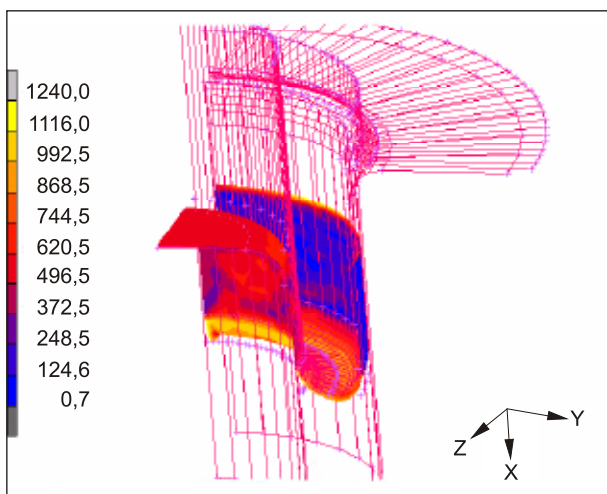


Figure 7. Equivalent Von Mises stress in working piece
Slika 7. Ekvivalentno Von Mises-ovo naprezanje u radnom komadu

full stress tensor at the last iteration, which results in the fastest convergence [7].

3D model was created. Fourth part is used, modeled by 3D membrane shell elements number 139. This is four nodes, thick shell element with global displacements and rotations. Bilinear interpolation is used for the coordinates, displacements and rotations. The membrane strains are obtained from the displacement field, the curvatures from the rotation field. The transverse shear strains are calculated at the middle of the edges and interpolated to the integration points. This 3D model is particularly interesting because wrinkling occurrence can be easily detected.

The main intention of a FEM simulation analysis was a detailed follow of material stresses and punch force behaviour through the deep drawing process in both draws. In that way the number of experiments could be reduced.

On the Figure 6. tool with its main parts is presented. The position of the parts is in third quarter of the process time.

The first interesting question in simulation analysis is behaviour of material stress in the point in which it reaches its greatest value. Figure 7. presents equivalent Von Mises stress in working piece. It shows both draws simulated using 3D membrane shell elements.

Minimal stress occurs on the top of the working piece, and it grows toward bottom of the working piece. Critical point is placed on the beginning of bottom round. On Figure 8. critical point in deep drawing processes is shown. Legend shows scale expressed in N/mm^2 .

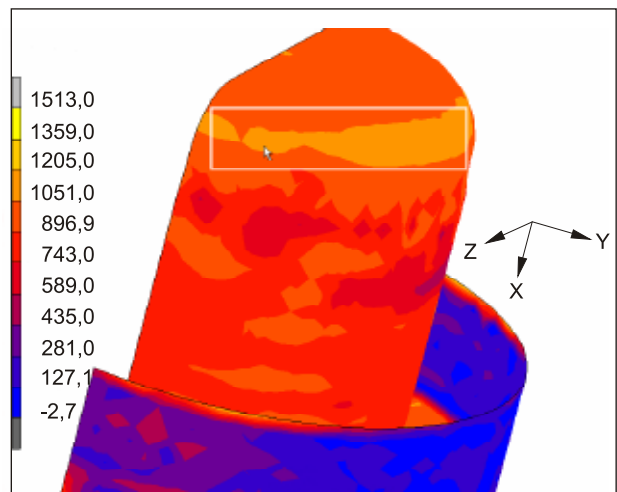


Figure 8. Critical point in working piece
Slika 8. Kritična mjesta na radnom komadu

The second question is behaviour of punch force and maximum of needed force for specific deep drawing process. On diagrams presented on Figure 9. and Figure 10. is the answer to the question. The axis x shows increments of simulation computing, that are set task. There are 100 incre-

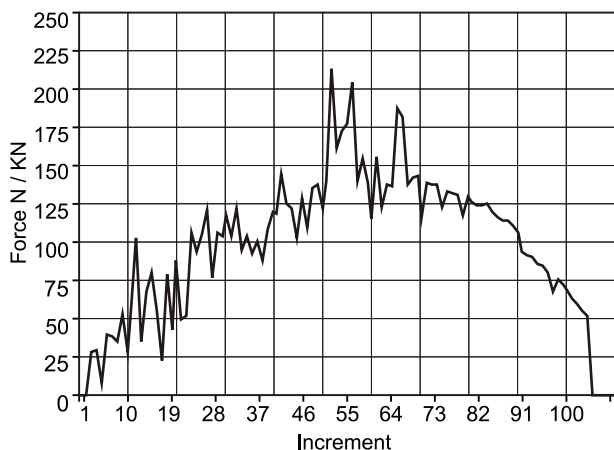


Figure 9. Calculated punch force in the first draw
Slika 9. Sila žiga u prvoj fazi dobivena numeričkom simulacijom

ments in working cycle and 5 increments in reciprocating motion. The axis y shows punch force expressed in N.

It is important to notice that maximal computed force in each draw is relatively close to the force got from the experiments.

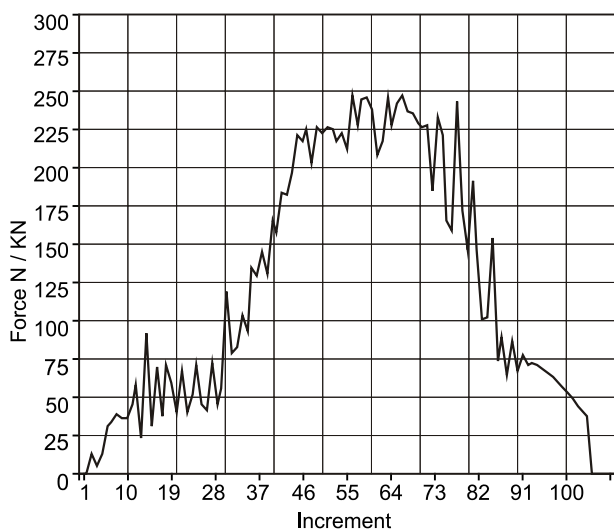


Figure 10. Calculated punch force in the second draw
Slika 10. Sila žiga u drugoj fazi dobivena numeričkom simulacijom

CONCLUSION

As it is presented, reduction in number of draws is solved by reversed drawing. Because of complexity of

the process and because of sensibility of the main parameters, FE modeling showed its best face. All the changes were done at first on the FE model, and after that on the experimental tool and part.

It is interesting to discuss results of punch force changing related to the reduction coefficient changing. By growing of reduction coefficient punch force decreases following a regression tendency curve. For the observed Cr-Ni stainless steel minimal reduction coefficient cannot go under 0,55 because the cracking occurs in the second draw. Punch force in the second draw is smaller, but by reduction coefficient changing, it also follows its own regression tendency curve.

Criterion of process success was avoidance of cracking occurrence. That is because by sticking to calculated process parameters no other problems took place [8].

Important occurrence that has to be notified is that reduction coefficient of 0,55 in a first draw is critical point in which all process parameters reach their critical value. That happens because of extreme hardening of material. This is the area that still needs to be improved by possible heat treatment.

Another thing that needs to be discussed is process simulation. By FE model creation and its processing we can read all the forces, displacements and stresses in process time. Punch motion was defined in increments. By observing each increment it is possible to have monitoring over all important process parameters as the process occurs. In this way all changes of parameters can be verified virtually before they happen in the real process.

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