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PART DIMENSIONAL ERRORS IN FREE UPSETTING DUE TO THE ELASTIC SPRINGBACK

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Original scientific paper

Elastic springback of workpiece material which occurs in any forming process has been recognized as one of most relevant factors regarding part dimensional accuracy. Therefore, in order to manufacture component in accordance with the geometrical specifications engineers must have a good understanding of this phenomenon and take it into account during the design tool and forming process. Unfortunately, this knowledge is often insufficient and therefore the prediction of elastic springback is sometimes a very tough task. The paper presents a general approach for the calculation of elastic recovery. Given analytical equations can be applied for different forming processes under the condition that values of the principal stresses at the very end of forming process are known. By using this approach elastic strains and amplitude of elastic springback of workpiece in case of free upsetting of cylindrical billet were calculated. Obtained results were verified by FEM analysis.

Keywords: *dimensional accuracy, elastic springback, free upsetting*

Dimenzijske greške kod dijelova dobivenih slobodnim prešanjem zbog elastičnog vraćanja materijala

Izvorni znanstveni članak

Pojava elastičnog vraćanja materijala radnog predmeta prisutna je u svim procesima plastičnog deformiranja metala. Ovaj faktor prepoznat je kao jedan od glavnih čimbenika dimenzijske (ne)točnosti. Stoga, da bi se proizveli dijelovi sukladno zahtjevima koji se odnose na njihovu geometriju ovaj fenomen se mora dobro razumjeti i uzeti u obzir prilikom projektiranja alata i procesa deformiranja. Nažalost, znanje vezano za ovaj fenomen je ograničeno te stoga predviđanje i proračun iznosa elastičnog vraćanja ponekad predstavlja vrlo težak zadatak. U ovom članku predstavljeno je opće analitičko rješenje za izračun elastičnog vraćanja. Izvedene analitičke jednadžbe mogu se primijeniti za različite procese oblikovanja pod uvjetom da su vrijednosti glavnih naprezanja na samom kraju procesa deformiranja poznate. Koristeći ovaj pristup izračunate su elastične deformacije i amplituda elastičnog vraćanja radnog komada kod procesa slobodnog prešanja cilindrične gredice. Dobiveni rezultati provjereni su pomoću MKE analize.

Ključne riječi: *dimenzijska točnost, elastično vraćanje, slobodno prešanje*

1 Introduction

In recent years, one of the main challenges forging industry has been faced with is to reduce production cost while increasing dimensional accuracy of final components. It forced many forgers to make a review of their traditional manufacturing procedures and to introduce new ones, such as net shape forming (NSF) technologies. But, achievement of parts with NSF (narrow) tolerances requires a number of factors affecting forming process to be well known especially their impact (individual and interrelated) on part accuracy [1, 2].

Final dimensions and overall dimensional accuracy of the formed parts is influenced by several factors [1, 3, 4]. Elastic behaviour of workpiece material after tool unloading (elastic springback) is one of them. Elastic spring back or material elastic recovery is an inevitable phenomenon of each forming process that affects change in workpiece volume and consequently deviation of part dimensions as systematic errors [5]. Unlike in design of sheet metal process where elastic springback of part is fully recognized and considered, in bulk metal forming this phenomenon is usually ignored by the process designers [3]. It comes from an old premise according to which elastic deformation during and after bulk forming process is generally too small compared to the plastic one and hence has no relevant effects on forming process. However, many of recent studies [3, 6, 7, 8] have clearly shown that elastic recovery of workpiece material significantly influences dimensional accuracy of cold formed parts. This is in particular emphasized in cases of components with narrow tolerances. Therefore, in order to eliminate the trial-and-error procedure and reduce part dimensional errors, elastic recovery of workpiece material should be considered when designing the forming process.

Driving force for material elastic recovery comes from the stresses generated in the workpiece during forming process. The level of this stress which depends mostly on material's properties, stress scheme (stress state) in workpiece, and, process conditions, determines the amount of elastic recovery part will experience [3, 8]. It means that any fluctuation in the stress level will result in variability of elastic recovery amount, i.e., lead to instability of part final dimensions which is another side effect regarding part accuracy.

There are several methods to predict and compensate springback dimensional errors at various industrial applications [3, 5, 6, 9]. Today, finite element (FE) simulation of forming [5, 7, 10] and other processes [11, 12, 13, 14] is mostly employed [5, 7]. Numerical simulation enables systematic approach to study elastic springback phenomenon. It provides quantitative information how various factors and process parameters affect this phenomenon including elastic strain distribution along workpiece after forming operation. Based on this prediction, the tools' geometry and process parameters are modified until part with the desired shape and dimensions is obtained. However, numerical analysis is not always able to accurately predict the springback of a formed part, so a discrepancy between the level of springback obtained in simulations and reality may be noticed; especially for the components with complex geometry [15, 16, 17]. Essentially, there are two reasons for poor springback prediction by FEM [5, 18]. The first one is that this phenomenon is not accurately represented in FE formulations. Various assumptions of material behaviour (constant elastic properties during forming, simplified elastic-plastic anisotropy, and work-hardening) may introduce large errors in the model. The second one is related to poor quality of modelling process itself (selected contact conditions and algorithms, method of unloading, material properties, element types, level of discretization etc.), which is caused by lack of proper input data.

Attempts to calculate elastic springback analytically are numerous [3, 5, 8, 19]. But, most of analytical solutions for elastic springback are derived only for simple bending and related sheet metal forming processes [5]. In the field of bulk metal forming similar analytical expressions are very rare so that in practice the simple form of Hooke's law is then used for the calculation [3]. It is a very rough approach leading to a substantial discrepancy between calculated and actual springback.

In this paper an analytical solution for prediction of elastic springback and final dimensions of part after forming process is presented. Derived from the general Hooke's law, this solution relates engineering strains with associated true stresses at the very end of forming process and can be applied to various deforming models regardless of stress-strain state in workpiece. Given analytical solution is applied to the case of free upsetting of cylindrical billet and validated by FEM analysis. Influence of certain parameters on the level of elastic springback was analysed as well.

2 General analytical solution for elastic springback calculation

Relation between deformations and stresses in elastic range is governed by Hooke's low [20, 21]. The generated Hooke's law (1) can be also employed for prediction of elastic springback and dimensions of part in directions of principal axes, but under condition of substituting engineering stresses that exist in the original Hooke's equations with true stresses at the very end of forming process (moment when tool starts to be released).

$$\begin{aligned}\varepsilon_{0,1} &= \frac{\sigma_{0,1}}{E} - \frac{\nu}{E}\left(\sigma_{0,2} + \sigma_{0,3}\right),\\ \varepsilon_{0,2} &= \frac{\sigma_{0,2}}{E} - \frac{\nu}{E}\left(\sigma_{0,3} + \sigma_{0,1}\right),\\ \varepsilon_{0,3} &= \frac{\sigma_{0,3}}{E} - \frac{\nu}{E}\left(\sigma_{0,1} + \sigma_{0,2}\right).\end{aligned} \tag{1}$$

$$\begin{aligned}\varepsilon_1 &= \frac{\sigma_1}{E} - \frac{\nu}{E}\left(\sigma_2 + \sigma_3\right),\\ \varepsilon_2 &= \frac{\sigma_2}{E} - \frac{\nu}{E}\left(\sigma_3 + \sigma_1\right),\\ \varepsilon_3 &= \frac{\sigma_3}{E} - \frac{\nu}{E}\left(\sigma_1 + \sigma_2\right),\end{aligned} \tag{2}$$

where are:

$\varepsilon_{0,1}$, $\varepsilon_{0,2}$, $\varepsilon_{0,3}$ – engineering (elastic) strains in directions of principal axes 1, 2 and 3

ε_1, ε_2, ε_3 – true strains

E – Young's (elastic) modulus

ν – Poisson's ratio

$\sigma_{0,i} = \dfrac{F}{A_{0,i}}$ – engineering stresses in directions of principal axes (i =1, 2 and 3)

$\sigma_i = \dfrac{F}{A_i}$ – true stresses in directions of principal axes

F – instantaneous force applied in forming process

$A_{0,i}$ – cross-sectional area before elastic deformation (initial area).

A_i – instantaneous cross-sectional area.

This simple procedure of replacing engineering with true stresses enables only approximate values of elastic springback to be obtained. Therefore, if one needs to predict elastic recovery of plastic deformed part more accurately a proper relationship between engineering stresses and corresponding true stresses at the elastic region of deformation has to be established. Starting from the basic link ($\sigma_{0,i} \cdot A_{0,i} = \sigma_i \cdot A_i$), and taking into account the change in the volume due to elastic recovery and relation between strains of principal directions ($\varepsilon_i = -\nu \cdot \varepsilon_{i+1}$), the required relationship can be derived by simple mathematical transformations (for more details see [3, 8]). The final expressions have the form:

$$\begin{aligned}\sigma_{0,1} &= \sigma_1(1+\varepsilon_2)(1+\varepsilon_3),\\ \sigma_{0,2} &= \sigma_2(1+\varepsilon_3)(1+\varepsilon_1),\\ \sigma_{0,3} &= \sigma_3(1+\varepsilon_1)(1+\varepsilon_2).\end{aligned} \tag{3}$$

After substituting (3) into equations (1) and simplifying the following system which relates elastic (engineering) strains and true stresses in elastic range is obtained:

$$\begin{aligned}\varepsilon_{0,1} &= \frac{1}{E}\left\{\sigma_1(1+\varepsilon_2)(1+\varepsilon_3) - \nu(1+\varepsilon_1)\left[\sigma_2(1+\varepsilon_2) + \sigma_3(1+\varepsilon_2)\right]\right\},\\ \varepsilon_{0,2} &= \frac{1}{E}\left\{\sigma_2(1+\varepsilon_3)(1+\varepsilon_1) - \nu(1+\varepsilon_2)\left[\sigma_3(1+\varepsilon_1) + \sigma_1(1+\varepsilon_3)\right]\right\},\\ \varepsilon_{0,3} &= \frac{1}{E}\left\{\sigma_3(1+\varepsilon_1)(1+\varepsilon_2) - \nu(1+\varepsilon_3)\left[\sigma_1(1+\varepsilon_2) + \sigma_2(1+\varepsilon_1)\right]\right\}.\end{aligned} \tag{4}$$

By solving the system (3) for the engineering strains ($\varepsilon_{0,1}$, $\varepsilon_{0,2}$, $\varepsilon_{0,3}$) and considering the basic equation that defines engineering strain, it is possible to determine the final dimension of a workpiece.

$$l_{0,i} = \frac{l_i}{\varepsilon_{0,i} + 1}. \tag{5}$$

In Eq. (5) l_i is the dimension when workpiece is under the load (function of forming operation) and $l_{0,i}$ is the dimension when the stress is no longer applied to the material (final part dimension).

System (3) has no solution for engineering strains in closed (analytical) form except for few cases (uniaxial stress state, plane strain state) therefore the numerical solving of the problem is obligatory. Regardless of this, analysing the system (3) some general insight into the sources and nature of the elastic recovery phenomenon can be gained.

The system of Eq. (4) confirms that stress state in workpiece at the very end of forming process directly determines the values of elastic strains and elastic springback. It is important to notice that not only stress level but also stress scheme i.e. stress character (tensile or compressive) influences the amplitude of elastic springback. Further, if we take into account the von Mises' yield criterion (6) and power law (7) [20]:

$$\sigma_e = \frac{\sqrt{2}}{2}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2} = k, \quad (6)$$

$$k = C \cdot \varphi_e^n, \quad (7)$$

it follows that true stresses are related with effective stress (σ_e) i.e. flow stress (k) which in turn is a function of plastic material properties (C, n) and the amount of effective (true) strain (φ_e). From (4 and 6) it is obvious that any rise of flow stress increases the values of engineering strains. At the same time, increase of the elastic modulus has opposite effect. In other words, the level of elastic springback depends on both elastic and plastic characteristic of workpiece material as well as forming process parameters. From the previous, some additional information regarding dimensional stability of part can be derived too. If we assume that in well controlled production by forming processes the value of effective strain is stable and that the Young's modulus for most metals remains unchanged during forming process it follows that variability in the engineering strain and associated elastic recovery comes only from the variability in flow stress and the plastic material properties respectively. It means that input data of material plastic properties can be used to estimate the distribution form of elastic springback [3, 8].

3 Analytical solution for elastic springback in case of free upsetting of cylindrical billet

In order to calculate elastic springback of free upsetting of cylindrical billet with flat dies, system (4) must be transformed. By using cylindrical coordinates for stresses and strains components and entering adequate stress state in the process of free upsetting (axially-symmetric stress state where $\sigma_1=\sigma_z$, $\sigma_2=\sigma_3=\sigma_r$, and $\varepsilon_1=\varepsilon_z$, $\varepsilon_r=\varepsilon_\theta$), system (4) is reduced to:

$$\begin{aligned} \varepsilon_z &= \frac{1}{E}\left\{\sigma_z(1+\varepsilon_r)^2 - 2\nu\sigma_r(1+\varepsilon_z)(1+\varepsilon_r)\right\}, \\ \varepsilon_r &= \varepsilon_\theta = \frac{1}{E}\{\sigma_r(1+\varepsilon_r)(1+\varepsilon_z) - \\ &- \nu(1+\varepsilon_r)[\sigma_r(1+\varepsilon_z)+\sigma_z(1+\varepsilon_r)]\}. \end{aligned} \quad (8)$$

In the next step, solved by an analytical form (or numerical system) the true stresses in workpiece for case of free upsetting of cylindrical billet should be inserted into (8). Here, from a few existing analytical solutions for contact stresses in process of free upsetting, the well-known Karman's expressions (9, 10) are chosen [20].

$$\sigma_z = k \cdot e^{\frac{2\mu}{h}(R-r)}, \quad (9)$$

$$\sigma_r = k \cdot \left[e^{\frac{2\mu}{h}(R-r)} - 1\right]. \quad (10)$$

After solving system (8) for engineering strains ε_z and ε_r, elastic springback in axial and radial direction is easily calculated by using the following expressions:

$$\begin{aligned} \Delta z &= \varepsilon_z \cdot h, \\ \Delta r &= \varepsilon_r \cdot r, \end{aligned} \quad (11)$$

where h and R denote the height and radius of the workpiece at the very end of forming process.

An analytical solution of the system (8) exists, but it is very complex and hence not suitable for practical use. From equations (9 and 10) it can be seen that both stresses increase toward workpiece axis of symmetry what suggests that greater elastic strains and corresponding dimension changes could be expected in this region as well. The sensitivity of the elastic strains to some process parameters (flow stress, friction), billet geometry (ratio R/h), and the position along the radial (r) direction are illustrated in Figs.1 ÷ 3. The results were obtained by inserting typical values for plastic and elastic properties of low carbon steel into equations (8, 9 and 10), as values for h and r were set equal to unity.

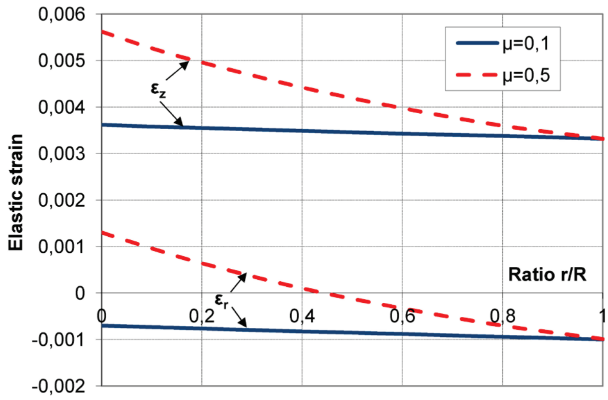

Figure 1 Distribution of elastic strains ε_z and ε_r against friction

The first thing to be noticed from these figures is variability of the elastic strain along workpiece radius hence contact surface will not be absolutely flat after tool removing. If upsetting is performed under condition of low friction (μ=0,1) the change of the elastic strains is not prominent (Fig. 1). But in opposite case (μ=0,5) amplitude of elastic springback varies significantly. Therefore, during upsetting processes with intensive friction which comes from either poor lubrication conditions or complexity of the tool geometry, differences in the workpiece height between central and outer zone may be noticeable. This difference increases even more when elastic springback is superimposed with tool elastic deflection being also greatest in the central zone. From previous it is clear that in order to improve part accuracy the friction should be reduced. The influence of ratio R/h

and flow stress k is similar – elastic springback level rises with increase of both factors (Fig. 2 and Fig. 3).

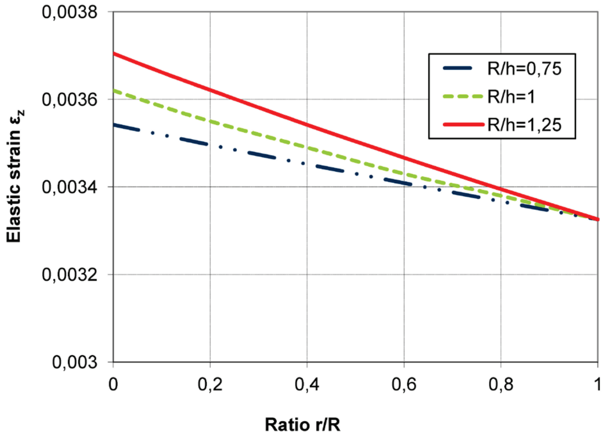

Figure 2 Distribution of elastic strains ε_z against ratio R/h

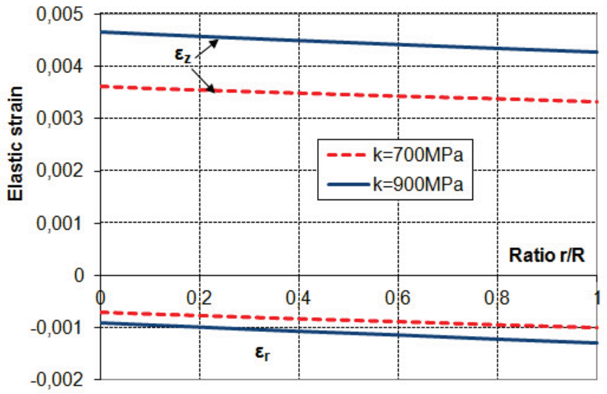

Figure 3 Dependence of elastic strains ε_z and ε_r of flow stress

In continuation analysis the free upsetting of cylindrical billet with initial dimensions of 20 × 25 mm under condition of low friction (μ=0,11) will be considered. Engineering strains and associated elastic recovery in axial (z) and radial (r) directions are calculated for three different values of the true (effective) strains (φ_e=0,4; 0,8 and 1,2). As workpiece material a low carbon steel C15E is chosen having flow curve in Ludwig's analytical form of $k = 309{,}15 + 409{,}57 \cdot \varphi_e^{0{,}518}$ (MPa), Poisson's ratio of ν=0,3, and Young's modulus of E=210000 MPa, respectively.

In order to verify the derived analytical solution for engineering strains, the upsetting process was also analysed by Finite Element Method (FEM). For that purpose a commercial software package Simufact.Forming.11 was used. In the simulation, tools were modelled as rigid bodies while the workpiece material was considered as elastic-plastic.

4 Analysis of results

For investigated upsetting process graphical interpretation of axial true stress σ_z along contact surface is given in Fig. 4. It can be observed that certain differences between analytical and FEM results for the stress values in centre of the workpiece exist, while the shape of distribution corresponds to a great extent. Therefore similar differences may be expected for the values of elastic strain.

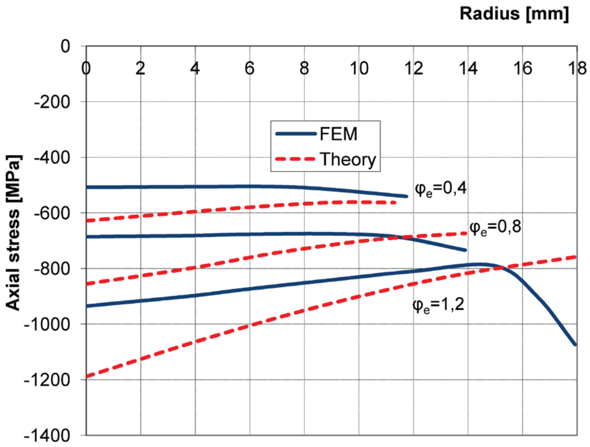

Figure 4 Distribution of axial contact stress

FEM results for equivalent elastic strain ($\varepsilon_{e,el.}$) for different values of effective plastic strain (φ_e=0,4, φ_e=0,8 and φ_e=1,2) are depicted in Fig. 5. As it can be seen, distribution of ($\varepsilon_{e,el.}$) within the workpiece volume is very heterogeneous and changes with equivalent strain.

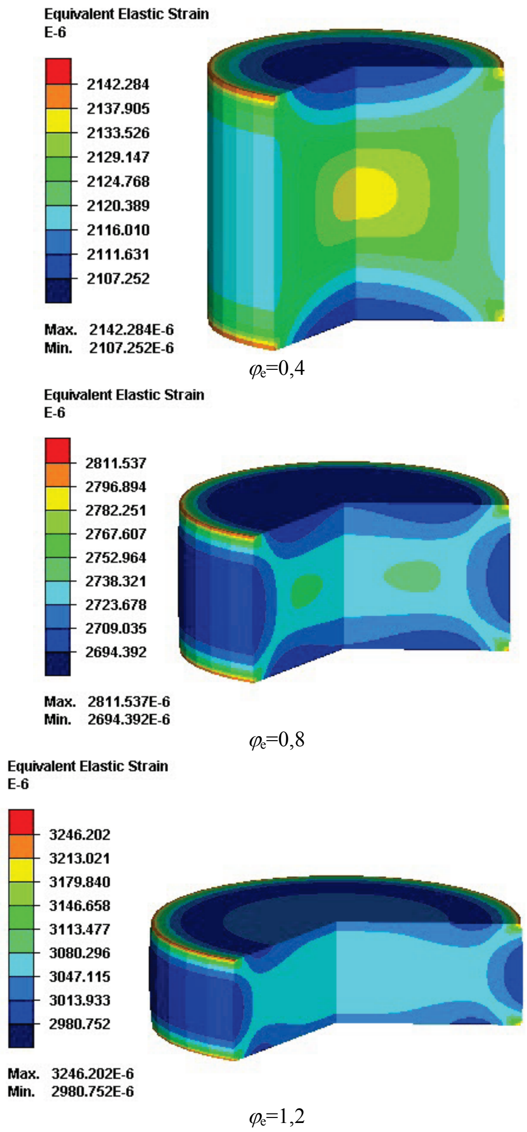

Figure 5 Distribution of effective elastic strain

Distribution of engineering strains in both axial ε_z and radial ε_r directions against workpiece radius is obtained analytically and by FEM simulation is given in Fig. 6 and Fig. 7. Both solutions indicate that the amplitude of the engineering strains depends very much on achieved degree of plastic deformation φ_e, what means that they are sensitive to the values of flow stress k and R/h ratio. It is evident that rise of the level of plastic deformation (flow stress and ratio R/h rise) the values of ε_z and ε_r increase too. Positive values of axial strain ε_z, suggest that the height of workpiece will be larger than before the tool unloading. At the same time, negative values for radial strain ε_r denote reduction of workpiece diameter. Also, it is noticeable that distribution of elastic strains corresponds to the one of true contact stresses. This is why analytical solution predicts slightly higher values for engineering strains compared to FEM analysis (max. 20 % in the workpiece center) as well as greater differences between maximum (r=0) and minimum (r=R) amplitudes.

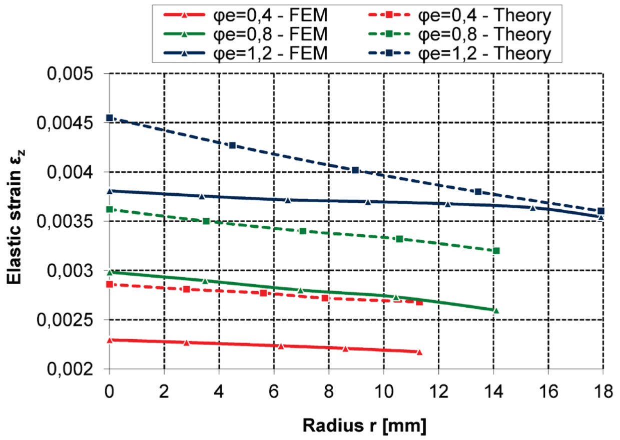

Figure 6 Distribution of axial elastic strain ε_z

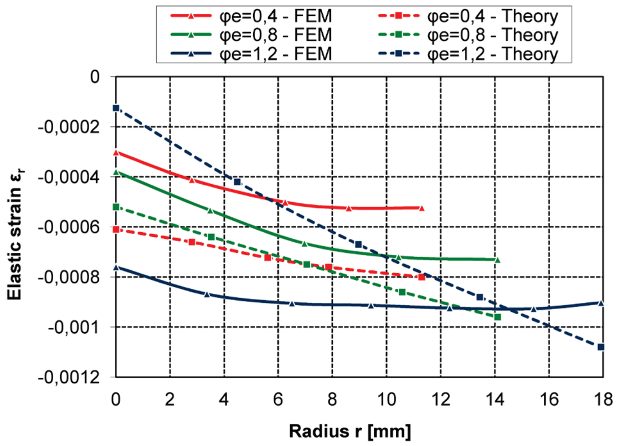

Figure 7 Distribution of radial elastic strain ε_r

Fig. 8 shows geometry of the part before and after tool release obtained by FEM simulation as Fig. 9 illustrates the change of the workpiece height (Δz) along the radius due to elastic springback (for the case of φ_e=1,2). As FEM analysis predicts a very slight difference in the amplitude of the elastic springback between the centre and outer zone, the difference is very sharp when observing analytical results (more than 5 µm). In real process (elastic tools), due to the superposition of strains, this difference may be 10 times greater [3].

In Fig. 10 maximum amplitudes for elastic springback in axial direction are shown for all three levels of effective plastic strain and related in terms of International Tolerance grade (IT) aimed to display the dimensional deviations more clearly. As it can be seen, the error in the workpiece height due to elastic recovery corresponds to IT9 ÷ IT10 grades, which could be considered as a significant loss of accuracy. In addition, it is very interesting to analyse the way how elastic springback decreases with increase of plastic deformation (Fig. 10). This trend is not linear as one might expect, but is represented with second-order curve.

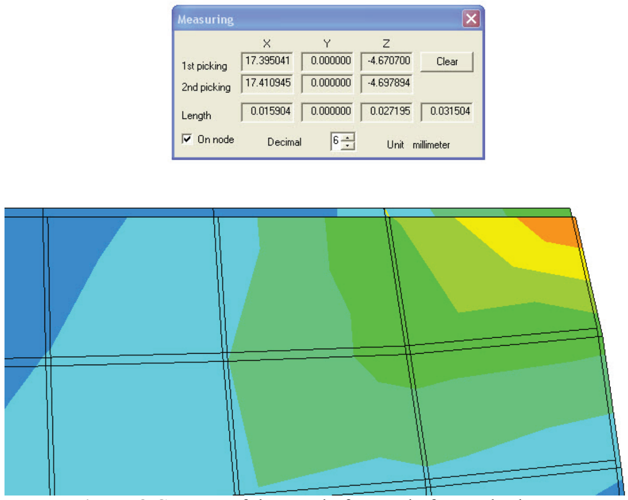

Figure 8 Contour of the part before and after tool release

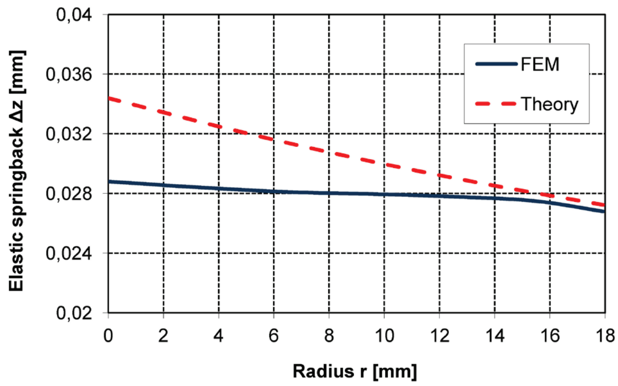

Figure 9 Elastic springback in axial direction

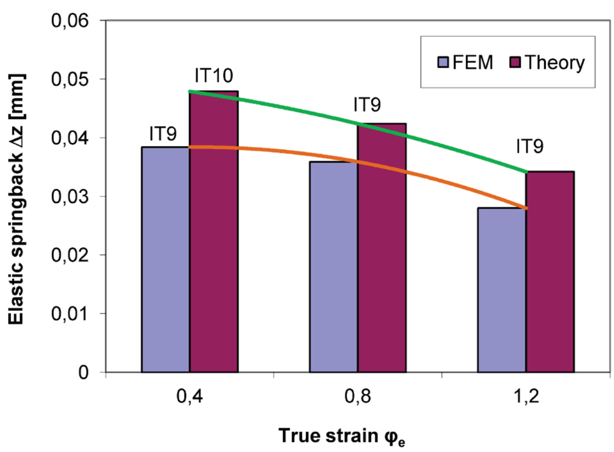

Figure 10 Maximum values of elastic springback

5 Conclusion

In the paper elastic springback was analysed in order to determine the quantitative influence of this phenomenon to part dimensional accuracy. For calculation of elastic springback a general analytical solution is given. It is derived from the general Hooke's law and relates principal engineering strains with principal stresses at the very end of forming process. Through this, it can be (theoretically) applied for any forming process. Analysing some parameters which exist in the equations, it was concluded that in well controlled forming processes fluctuation of flow stress is the major cause of part dimensional instability.

The analytical solution was tested in case of free upsetting of cylindrical billet and verified by FEM simulation. Analytically and FEM predicted values for elastic springback show good agreement. Obtained results suggest that elastic springback affects significantly the dimensional accuracy in free upsetting where error may reach IT9-IT10 grades.

Generally it could be said that accuracy of analytical results depends directly on the reliability of analytical equations (data) for the stress components in analysed forming process. Due to relatively simple form of the equations, elastic springback can be quickly calculated which can improve the efficiency of design procedure.

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