Simulation of forging of lids with different upper tools

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Abstract

In this work, numerical simulations of selected steps of the manufacturing of copper lids (for use as part of copper canisters for used nuclear waste) have been treated. All numerical FE-simulations have been conducted using the commercial software LS-Dyna 971 using 2D-axisymmetric models. The main aim has been to study the plastic strain evolution in the workpiece material during the manufacturing of the lid. This to find and suggest improvements to parts of the manufacturing process and/or tool designs. It is of highest importance that the plastic strains within the workpiece during the manufacturing are high enough to secure recrystallization and a fine grained microstructure. The method used for the manufacturing of the lid (prior year 2013) will serve as a reference production method. If the intrusion depth is increased from the original 190 mm to 320 mm during step 3, the effective plastic strain in the area of interest increases to 0.8 (from 0.16) with 139 mm minimum workpiece thickness remaining at the bottom.

Content

1 Introduction

In this work, numerical simulations of selected steps of the manufacturing of copper lids as part of copper canisters for spent nuclear fuel have been treated. The main aim has been to study the plastic strain evolution in the workpiece material during the manufacturing of the lid. This to find and suggest improvements to parts of the manufacturing process and/or tool designs. It is of highest importance that the plastic strains within the workpiece during the manufacturing are high enough to secure recrystallization and a fine grained microstructure. The method used for the manufacturing of the lids (prior year 2013), in the following called the reference method, comprises a number of steps that briefly will be described below. The lids referred to in this work were manufactured at Scana steel in Björneborg Sweden and has the identities TX207 to TX216, see "Tillverkning av kapselkomponenter" (SKBdoc 1175208).

1. Furnace heating to ~780 °C of an initial cylindrical workpiece with a diameter and height of 500 and 739 mm (cold dimensions), respectively. The billet mass is 1,300 kg.
2. Upsetting of billet, where the billet is reduced by 290 mm from its initial hot height, 749 mm, to 459 mm while pressing it between two planar tool parts (upper and lower), see Figure 1-1.
3. Pressing a tool according to Figure 1-2 and Figure 1-3 into the workpiece by ~190 mm.
4. Closed die forging by using a flat upper tool. In this step the workpiece is pressed into the cavity of the lower tool. The force available in the hydraulic press used is limited to 4,500 tons, which is insufficient to completely fill the workpiece into the cavity of the lower tool (not giving the workpiece its final form).
5. Cogging of the workpiece with the upper tool illustrated in Figure 1-4.
6. After cooling to room temperature, the workpiece is machined to its final dimensions.

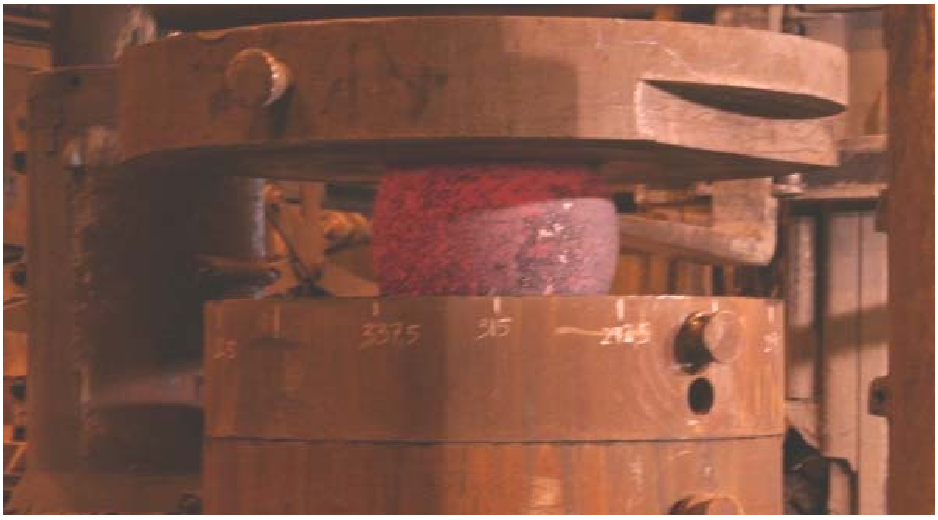

Figure 1-1. *Upsetting of the workpiece in the reference process.*

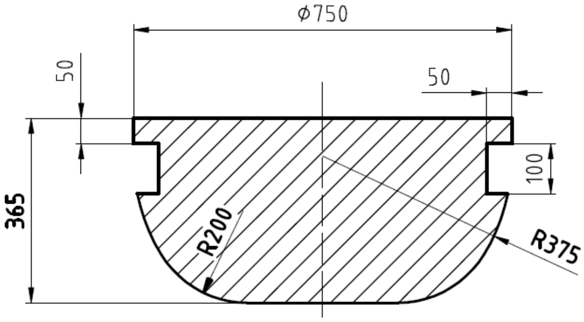

Figure 1-2. *Tool used in the step before closed die forging.*

Figure 1-3. *The state where the upper tool is pressed 190 mm into the workpiece.*

Figure 1-4. *Cogging with tools and workpiece shown.*

In this work, the steps 2-3 in the reference method have been simulated to study the plastic strains in the workpiece. It is important to check and possibly increase these strains in certain areas of the manufactured lid where a coarse microstructure (large individual grains) has been detected in ultra-sonic inspections. Then some modifications/changes to the reference method has been simulated and evaluated as well as the use of alternative upper tools for step 2 and 3 (performed in one step). The ingot that is heated to 780 °C in the furnace in step 1 is estimated from measurements to have an average temperature of 750 °C when the actual pressing begins. Three variants of the upper tool have been evaluated in means of calculated forming force and plastic strain distribution when reducing the initial 750 °C hot ingot in height preceding the closed die forging.

2 FE-model descriptions

The FE-simulations performed have been conducted using the commercial software system LS-DYNA 971R6, Hallquist (2006). All simulations have been performed thermo-mechanically coupled. In LS-Dyna, the coupling is performed using a staggered approach, meaning that the thermal step precedes the mechanical steps and the thermal field is calculated based on the previous (converged) mechanical configuration. All LS-DYNA simulations have been performed using an explicit time integration scheme and a fully implicit (iterative) thermal solution procedure. All cases studied have been modeled as 2D-axisymmetric, meaning that the problem is assumed not to have any variations in the circumferential direction. This means that any variations in either temperature or friction in that direction cannot be modeled and simulated. Further, effects on the workpiece behavior (plastic flow, shape etc.) due to variations in tool shape or initial workpiece geometry along the circumference direction cannot be studied. The angular dimension of the axisymmetric model used is one radian and in order to obtain the total forming force a multiplication of 2π radians is necessary.

2.1 Elements and contacts

The element variant used in LS-DYNA in the case of 2D-axisymmetric simulations is the Type 15 volume weighted axisymmetric Galerkin element for both the rigid tool parts and the workpiece. In LS-DYNA, penalty based contacts have been employed and the contact is an automatic variant called *CONTACT_2D_AUTOMATIC_SURFACE_TO_SURFACE_THERMAL, in which the thermal heat transfer across the contact interface is used. The thermal contact is set to be active if the distance between the contacting instances not are greater than 0.1 mm and the heat transfer is regarded not to be pressure dependent, as in “Process simulation of large copper extrusions” (SKBdoc 1351636). The heat transfer conductance used has been adapted from the same report.

2.2 Friction

The friction model used for the contacts is of Coulomb type. In the current work the static and dynamic coefficients of friction have been set equal to 0.2 meaning that the frictional coefficient is regarded as constant independent of the relative sliding velocity. In order to limit the maximum shear stress (force) in the contacts from reaching unrealistic levels, a constant upper limit value of 6 MPa has been chosen. This is based on “Main study - copper tube extrusion” (SKBdoc 1377246) for lubricated contacts.

2.3 Constitutive models

The mechanical constitutive laws used in LS-DYNA is an elastic-(visco)plastic model with strain rate and temperature dependent hardening curves for the workpiece material. The workpiece hardening data (stress versus strain data) used is taken from “Control and effects of grain size in extruded copper” (SKBdoc 1265008). During the different deformation processes, 90 percent of the plastic work is assumed to be converted into heat.

All tool steel parts are modeled as rigid, and the thermal data corresponds to tool steel material 34CrNiMo6. The thermal material model used (both for tools and work-piece) is an isotropic thermal model with temperature dependent thermal conductivity and specific heat.

2.4 Lower tool

The lower tool model is based on the geometry of the production tool which is used 2013.

3 Simulations and results

In this section the simulations performed using the reference production method, steps 2-4 described in the introduction section together with simulations using variants of the upper tool. Estimated forming forces during the forming steps as well as the plastic strain evolution and distribution are treated here. In all the simulations performed, a press speed of 70 mm/s (for the upper tool) has been used, which is taken from Ssemakula (2004).

3.1 Reference method

In the reference method described previous, the force versus displacement during step 2 and 3 are shown in Figure 3-1. As can be observed, the maximum force for the upsetting is close to 1,410 ton at a reduction in height of the workpiece by 290 mm. After the simulation of step 2, a thermal only simulation has been performed to include the cooling of the workpiece placed on the lower tool for 120 seconds, based on observations from the process. The temperature distribution of the workpiece is then used as start for the third step. The temperature of the workpiece after the 120 seconds cooling period is shown in Figure 3-2. For the third step (piercing), simulations have been performed both with and without the effective plastic strains from the preceding upsetting operation. This is due to the uncertainties regarding the copper ability to recover plastic strains at the temperatures in question. It can be noticed here that the necessary force needed to perform the operation is lower for the non-strained material until a stroke of 90 mm is reached, then the force levels for the two variants are almost identical. Note that the stroke for the upper tool during step 3 is limited to 190 mm and a maximum force close to 2,000 ton. Here a maximum stroke of 389 mm has been used to study the force and plastic strain evolution during the process (and for comparison purposes). For step 2 the maximum effective plastic strain within the workpiece reaches 0.9 the center part and 0.06 in its bottom and top center regions (blue) closest to the tools according to Figure 3-3.

The effective plastic strain distributions after a deformation depth of 190 mm with the tool shown in Figure 1-2 and Figure 1-3 are illustrated in Figure 3-4 and Figure 3-5. For the case where the plastic strains are inherited from the previous deformation stage (upsetting), the maximum effective plastic strain becomes 1.856 and at the bottom (center of lower surface) it is as low as 0.16 (Figure 3-4). The corresponding effective plastic strains for the case without strains inherited from step 2 become 0.91 and 0.14 (Figure 3-5). Continuing the deformation of the workpiece in step 3 until minimum 70 mm of the workpiece thickness remains gives effective plastic strains according to Figure 3-6 and Figure 3-7. In Figure 3-8 the effective plastic strain evolution of the lower center elements (in Figure 3-6 and Figure 3-7) as function of the intrusion depth are plotted. Here we can see that the effective plastic strain doubled from 0.2 at a stroke of 200 mm up to 0.4 at 250 mm's stroke. For the closed die forging (step 4), the minimum effective plastic strain within the workpiece is close to 0.65, as illustrated in Figure 3-9 (plastic strains kept from previous steps) at the stage where the press force is close to 4,600 ton.

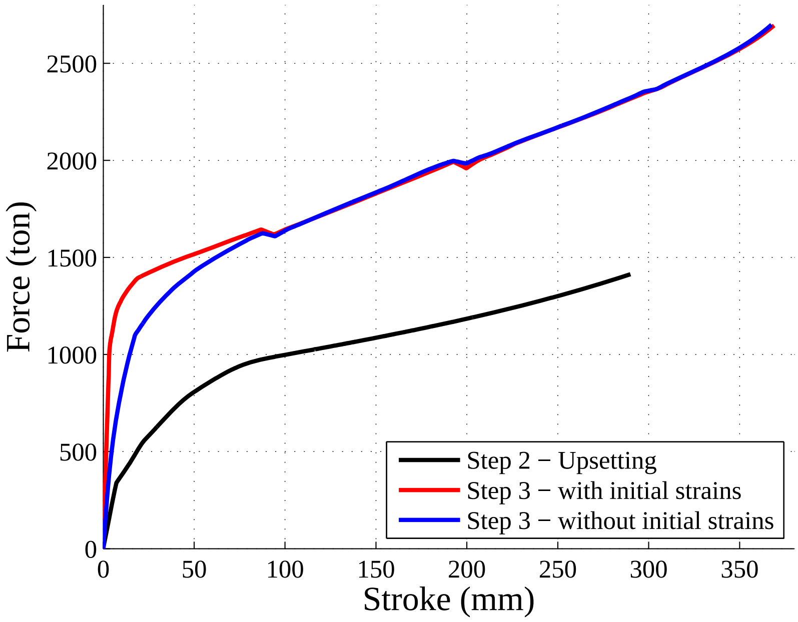

Figure 3-1. *Force versus stroke for the reference steps 2 (upsetting) and 3 (piercing).*

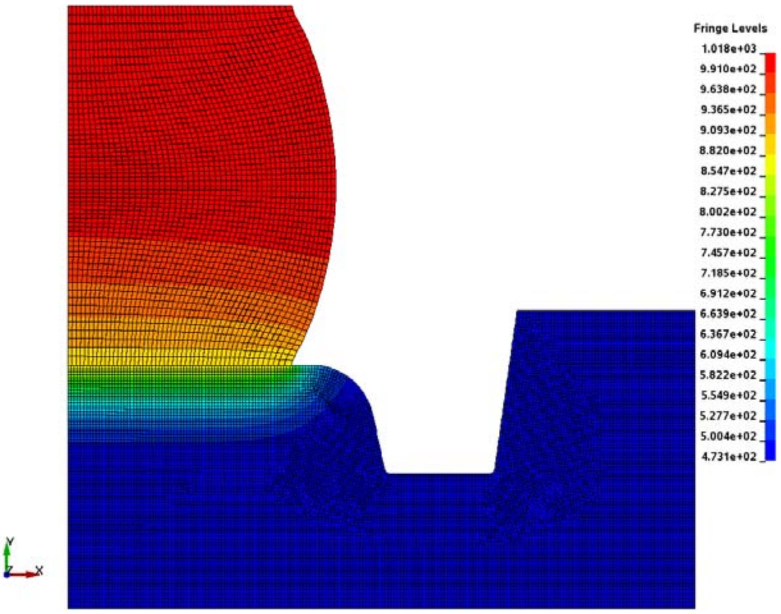

Figure 3-2. *Temperatures after 120 seconds cooling between step 2 and 3. Note that the temperature is given in Kelvin.*

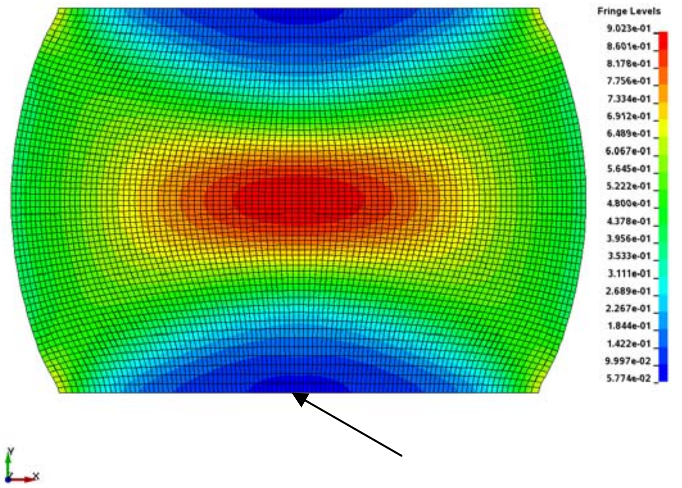

Figure 3-3. *Effective plastic strain distribution after the upsetting operation. The model is mirrored in the yz-plane.*

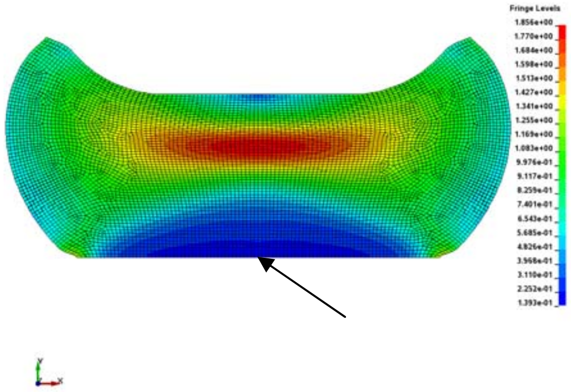

Figure 3-4. *Effective plastic strain distribution for the case where plastic strains are inherited from the previous step. An intrusion depth of 190 mm is applied during step 3.The arrow illustrates the lower center element referred to in the text. The model is mirrored in the yz-plane.*

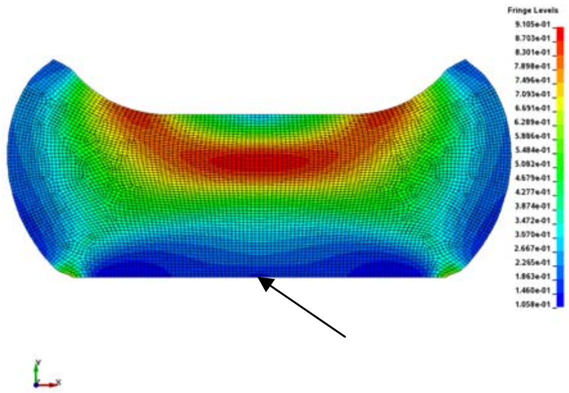

Figure 3-5. *Effective plastic strain distribution for the case where no plastic strains are inherited from the previous step. An intrusion depth of 190 mm is applied during step 3. The arrow illustrates the lower center element referred to in the text. The model is mirrored in the yz-plane.*

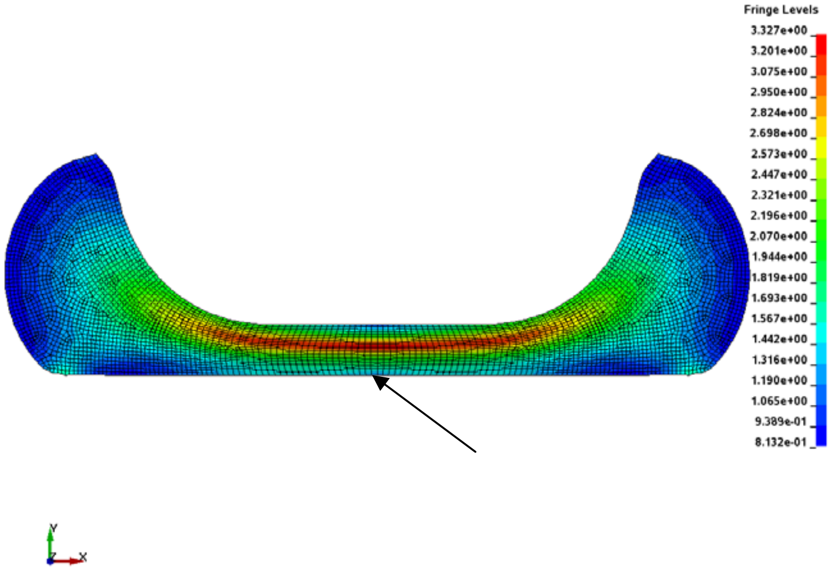

__Figure 3-6.__ Effective plastic strain distribution for the case where plastic strains are inherited from the previous step. An intrusion depth of 389 mm is applied during step 3 (minimum 70 mm remains). The arrow illustrates the lower center element referred to in the text. The model is mirrored in the yz-plane.

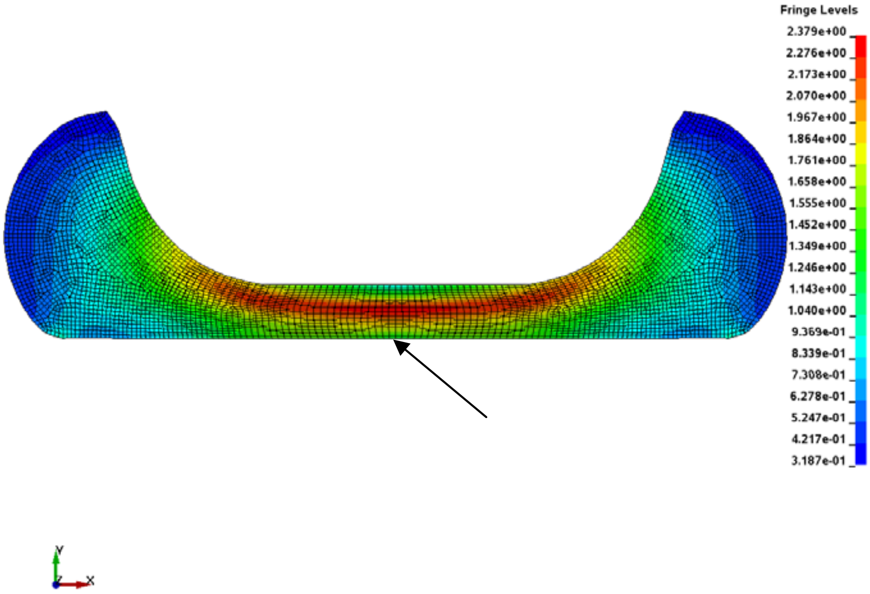

__Figure 3-7.__ Effective plastic strain distribution for the case where plastic strains not are inherited from the previous step. An intrusion depth of 389 mm is applied during step 3 (minimum 70 mm remains). The arrow illustrates the lower center element referred to in the text. The model is mirrored in the yz-plane.

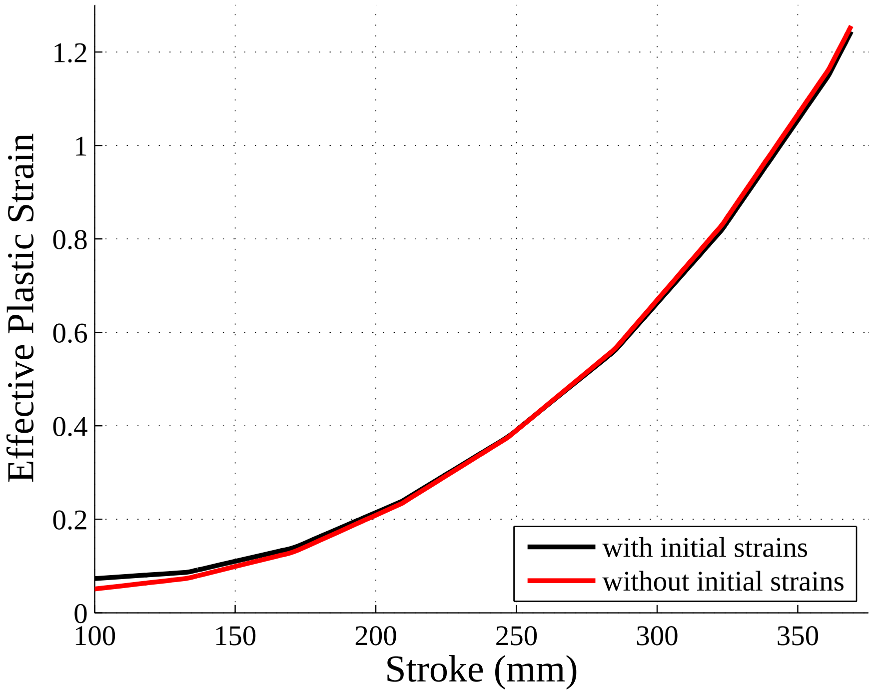

Figure 3-8. *Evolution of effective plastic strains in the elements illustrated by arrows in Figure 3-4 and Figure 3-5 during the deformation in step 3.*

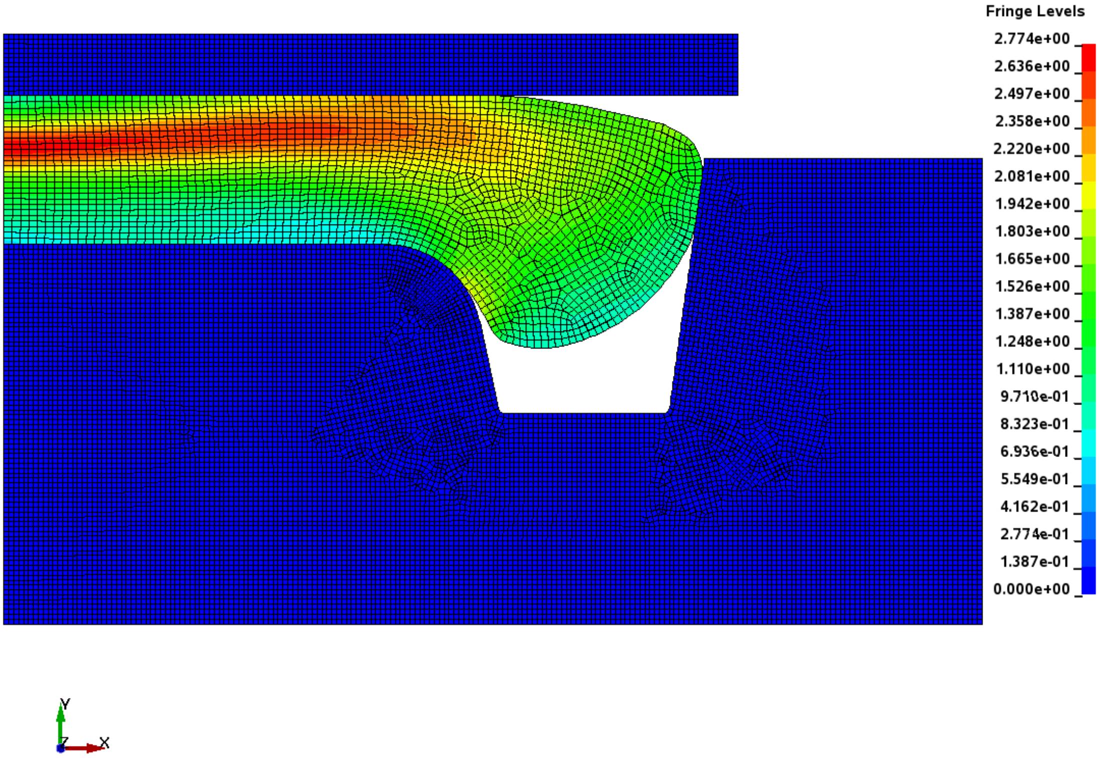

Figure 3-9. *Effective plastic strain distribution for the reference method - step 4, closed die forging, at the final state where a maximum press force of 4,600 ton is reached.*

4 Discussion and conclusions

As seen from the simulations of the reference process, the maximum plastic strain reaches 0.06 for an element illustrated in Figure 3-3 during the upsetting. The corresponding element reaches the effective plastic strains of 0.16 and 0.14 after step 3 at an intrusion depth of 190 mm when the strains from the previous step have been inherited or not. This level of the effective plastic strains is too low to ensure a fine grained microstructure if comparing to the experimental work performed in “Control and effects of grain size in extruded copper” (SKBdoc 1265008). For an average strain rate of ~0.1 s^{-1} at 750 °C as in the current work, it has been shown in “Control and effects of grain size in extruded copper” (SKBdoc 1265008) that an initial grain size of 367 µm end up as ~180 µm after a strain of 0.1 followed by quenching to room temperature after a 5 second long holding period. In the actual process, the grain growth continues unless further straining or rapid cooling to lower temperatures occurs. The grain growth during the first 1,000 seconds (16.7 minutes) after a deformation (strain) of 0.3 at the temperature 750 °C with a strain rate of 0.1 s^{-1} is relative rapid, an initial 65 µm grain end up as 300 µm in size (SKB 2013). As reported in “Tillverkning av kapselkomponenter” (SKBdoc 1175208) large grains have been detected in the center lower region. This indicates a combination of low plastic strains, initial large grains and a long time at high temperature which promotes the grain growth. Increasing the deformation depth in step 3 gives a rapid increase in the effective plastic strain level reaching 0.4 and 0.65 after the intrusion depths 250 and 300 mm, respectively. It should not cause any problems regarding the force level, ~2,400 ton needed, to increase the deformation depth to 300 mm in step 3. A possible disadvantage of increasing the intrusion depth may be the difficulty of keeping a good tool centering throughout the forming operation. It should be noted that no information is available to the author’s knowledge regarding the initial grain sizes and distribution within different regions of the initial workpiece. Therefore we cannot give any predictions of the grain sizes obtained in the actual lid manufacturing process for different strain levels.

References

Hallquist J O, 2006. LS-DYNA theory manual. Livermore, CA: Livermore Software Technology Corporation.

Ssemakula H, 2004. Manufacturing of heavy rings and large copper canisters by plastic deformation. PhD thesis. Royal Institute of Technology, Sweden.

Unpublished documents

SKBdoc id, version	Title	Issuer, year
1175208, ver 5.0	Tillverkning av kapselkomponenter.	SKB, 2009
1377246, ver 2.0	Main study - Copper tube extrusion.	SKB, 2013
1351636, ver 3.0	Process simulation of large copper extrusions.	SKB, 2012
1265008, ver 2.0	Control and effects of grain size in extruded copper.	SKB, 2013