FINITE ELEMENT SIMULATION OF OPEN DIE FORGING PROCESS WITH DIFFERENT DIE GEOMETRIES: INTERNAL VOID CLOSURE IN LARGE INGOTS[1]

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Abstract

Finite element simulations were used to analyze the effects of different die geometries in open die forging. Emphasis is placed on the mechanism of internal void closure and a comparison is made between different die geometries in terms of effective strain, metal flow and press load. The finite element code DEFORM™ 3D was used to investigate the following die geometries: plate die, dished die and swage die. Temperature and geometry, forging equipment and environment temperature were similar to those used in real process conditions. Other parameters, required in the simulations, such as the thermo-mechanical relationship between die and ingot, and a number of material properties, were found in the literature. For each die geometry the maximum press load, top die stroke and maximum effective strain localization at the time of total void closure are reported. The results of this study show that the most effective die geometry regarding internal void closure depends on the region of frictional constraint metal flow and maximum press load capacity.

Key words: Finite element method; Open die forging; Large ingots; Internal void.

SIMULAÇÃO POR ELEMENTOS FINITOS DO PROCESSO DE FORJAMENTO EM MATRIZ ABERTA COM DIFERENTES GEOMETRIAS DE MATRIZES: ELIMINAÇÃO DE VAZIOS INTERNOS EM GRANDES LINGOTES

Resumo

Simulações por elementos finitos foram utilizadas para analisar os efeitos de diferentes geometrias de matrizes em forjamento em matriz aberta. A ênfase deste trabalho foi dada ao mecanismo de eliminação de vazios internos, através da comparação entre diferentes geometrias de matrizes, em termos de deformação efetiva, fluxo de metal e força da prensa. O código de elementos finitos DEFORM™ 3D foi utilizado para investigar as seguintes geometrias de matrizes: matriz plana, matriz côncava e matriz curva. Os valores de temperatura e dimensão do lingote, equipamento de forjamento e temperatura ambiente são os mesmos que ocorrem no processo real. Outros parâmetros necessários para a simulação, tais como relações termomecânicas entre matriz e lingote, e propriedades do material foram obtidos da literatura. Para cada geometria de matriz, relatou-se a força máxima da prensa, curso da matriz superior e local de máxima deformação efetiva no instante da eliminação do vazio. Os resultados deste estudo mostram que a geometria de matriz mais efetiva, considerando a eliminação de vazios internos, depende da região de fluxo de metal restringido e da capacidade máxima da prensa.

Palavras-chave: Método de elementos finitos; Forjamento em matriz aberta; Grandes lingotes; Vazios internos.

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INTRODUCTION

Open die forging is an important process to manufacture large parts such as electric generator shafts to the power generation industry and steel blocks to manufacture large plastic moulds. This process improves ingot mechanical properties and eliminates internal voids that result from the solidification process of large ingots.(1-7)

Electric generation shafts must meet several requirements of internal quality to avoid fatal failure. Also, steel blocks to plastic moulds should be free of internal porosity to assure good finished mould surface. Therefore, it is important produce large parts with optimum internal quality. The part internal quality depends on the sequence of operations, process parameters, die geometries, forging press capacity, etc(5). In forging large ingots, it is difficult to achieve sufficient internal deformation for void closure, especially, when there are limitations in forging equipment.(3)

Internal void closure in large ingots was studied since the first half of the last century. Tomlinson and Stringer(8) investigated internal void closure by upsetting process using steel blocks containing machined holes. Other researchers analyzed this issue by cogging process using steel blocks and plasticine.(1,2) Nowadays, with the numerical computation evolution, the numerical modeling of forging processes by the finite element method (FEM) has became common in the design and development of forging processes.(9,10) Particularly, FEM has been used to study the mechanism of void closure by cogging process. Papers investigated cogging process parameters such as bite ratio, forging reduction, die and billet geometry, die width ratio and number of passes. The focus was to optimize process parameters to forge ingots with 50 to 200 tons using press loads of 10,000 to 50,000 tons.(4)

In this study, a commercially 3D finite element code, DEFORM™ 3D, is used to simulate upsetting operations with three die geometries: plate die, dished die and swage die. Emphasis is placed on the mechanism of internal void closure in 25 ton ingot by upsetting process. To simplify the analysis, only the initial press stroke was simulated, because the initial stroke is considered to be most critical for producing a sound forging when the internal void is closed.(5)

FINITE ELEMENT SIMULATION

The finite element simulation employed a rigid-viscoplastic formulation with thermo-mechanical coupling parameters. Due to the ingot symmetry, only one half of the ingot and die was modeled.

In order to understand the mechanism of internal void closure, nine numerical simulations were conducted. For each die geometry (plate die, dished die and swage die), the simulation was carried out with three types of ingot. The basic ingot geometry is a frustum of a cone which has main dimensions comparable to those of ingots used in industry. In the first ingot type, it was included an artificial void represented by a hemisphere with 80 mm diameter localized in the upper position. The second ingot type has the same artificial void localized in the lower position. The last ingot type is free of voids and was used to analyze the effective strain distribution without void influence. Figure 1 shows the details for ingots with void localized at the upper and lower positions whereas Figure 2 illustrates die geometries.

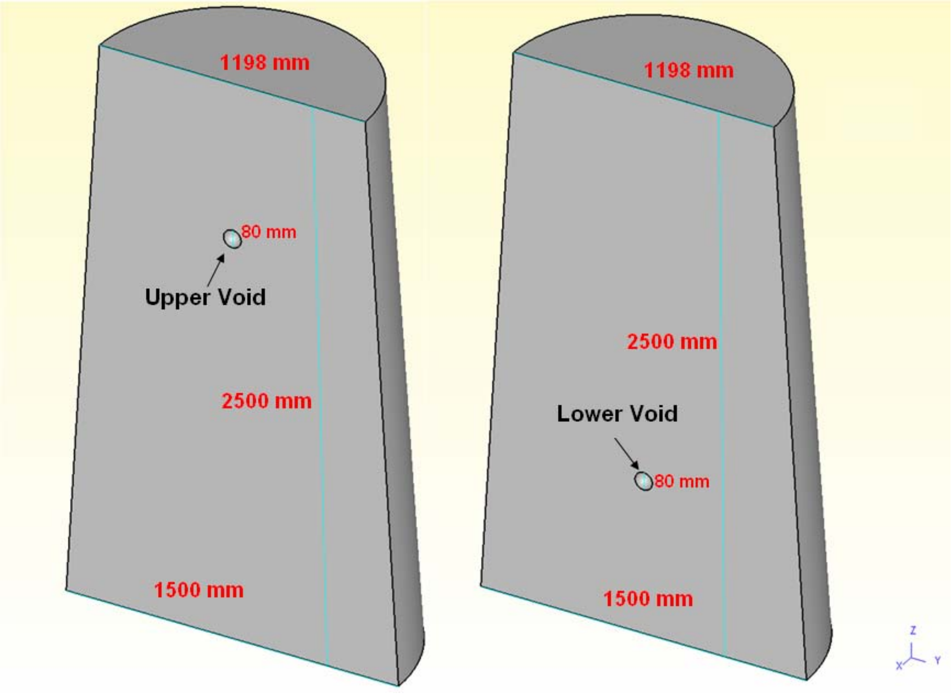

Figure 1- Ingot geometries and void localizations.

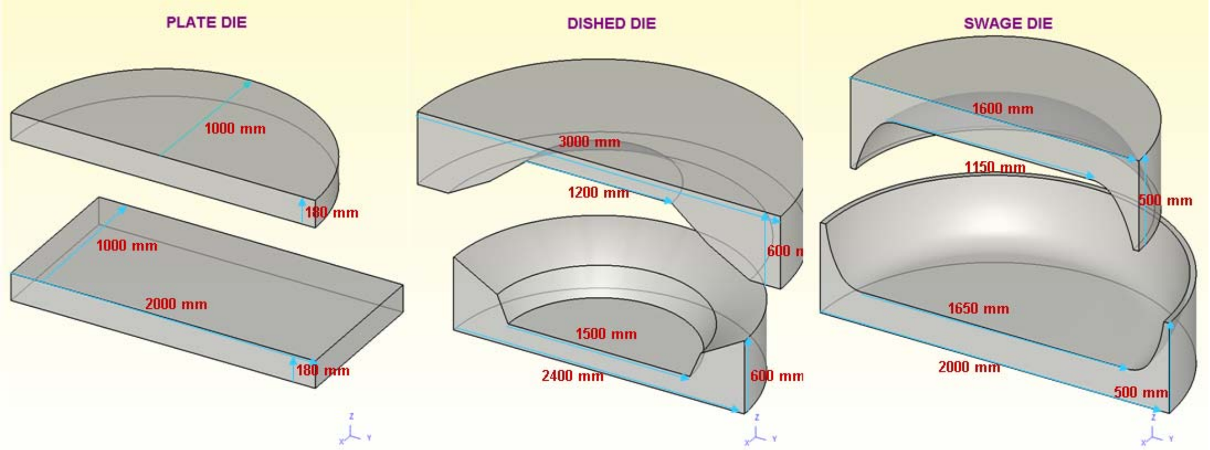

Figure 2- Die geometries with the respective main dimensions.

The thermo-mechanical properties of the materials used in the numerical simulations were supplied by the DEFORM 3D library. The ingot material was AISI 4340 whose flow stress $(\overline{\sigma})$ was characterized as a function of strain $(\overline{\varepsilon})$, strain rate $(\dot{\overline{\varepsilon}})$ and temperature (T) $(\overline{\sigma} = f(\overline{\varepsilon}, \dot{\overline{\varepsilon}}, T))$. Die material was AISI H13 with rigid condition. Additional thermal properties are listed in Table 1.

Table 1- AISI 4340 and AISI H13 thermal properties.

Properties	AISI 4340	AISI H13
Thermal Conductivity	24.8~32.9 W/m°C	24.2~24.7 W/m°C
Heat Capacity	4.3 N/mm^2°C	2.8~7.4 N/mm^2°C
Emissivity	0.7	0.7

Simultaneous heat transfer and deformation analyses were performed. The room temperature was 30°C, the ingot initial temperature was 1260°C and was assumed 60°C for die initial temperature. The convective heat transfer coefficient on the free surfaces was estimated to be 10 W/m^2°C for ingot and dies. At the contact region between the ingot and the dies, the interface heat transfer coefficient was 11 kW/m^2°C and the shear friction coefficient (m) was set 0.7.

The forging equipment was considered as a hydraulic forging press and it was adopted a speed versus top die stroke curve (Figure 3) obtained from a upsetting forging process of a 25 ton ingot carried out on plate dies with a 3,000 ton hydraulic press.

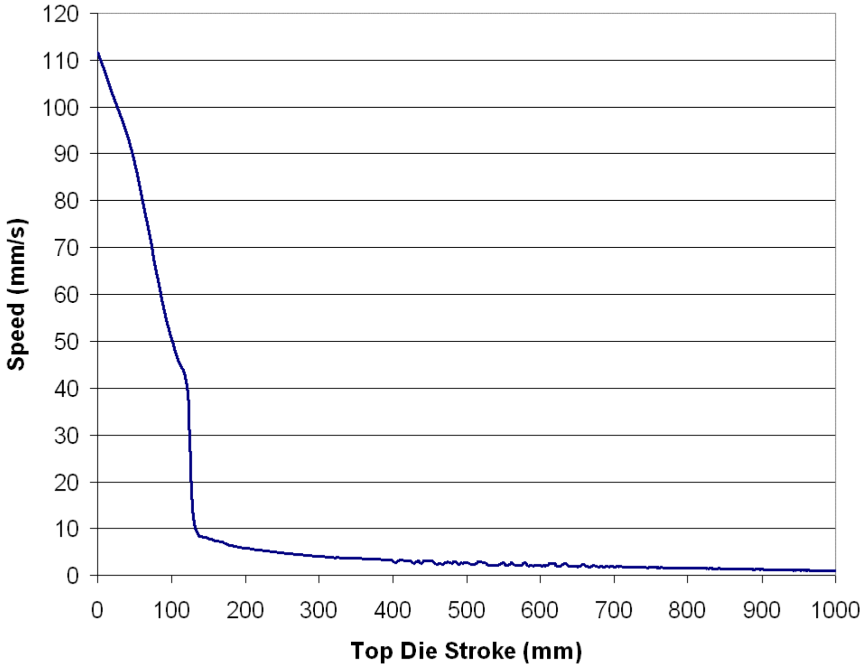

Figure 3 - Speed versus top die stroke curve.

For all simulations, it was assumed 1,000 mm for the total top die stroke that was divided into 250 steps of 4 mm. In the numerical calculation, it was used a conjugate-gradient solver with direct iteration method to solve the finite element system of equations.

VOID CLOSURE PARAMETERS

In order to predict the ingot internal quality with finite element simulations it was necessary to define parameters to determine when the void closure occurs. Throughout the visualization of simulation graphics, it was observed the moment when all void nodes on the ingot symmetry surface come to contact. Figure 4 shows a schematic of this void closure moment.

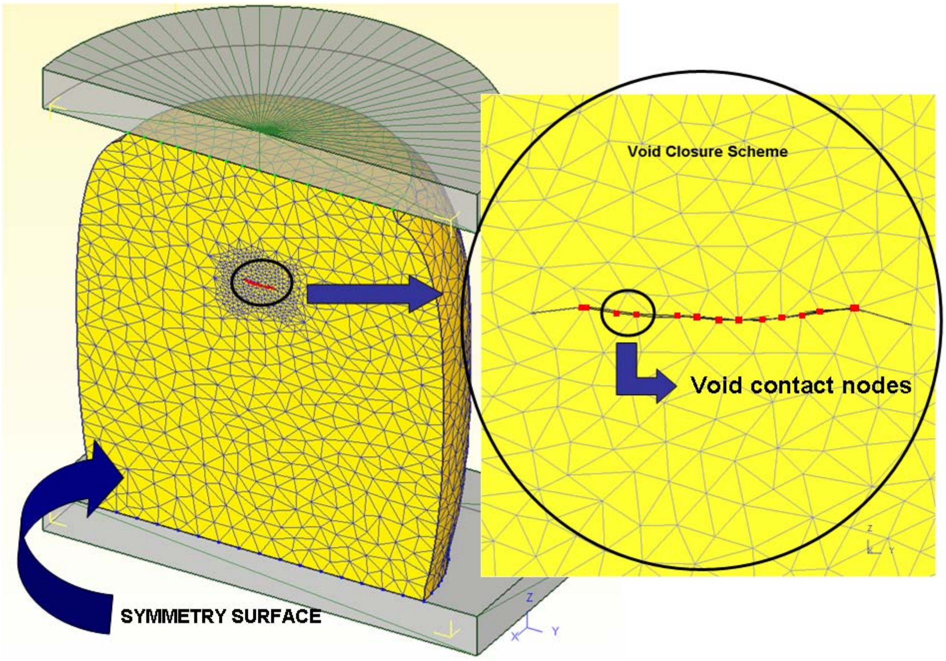

Figure 4 - Representation of complete void closure.

In the case where complete void closure was not reached, a void closure ratio vc_r was defined according to Equation (1):

$$vc_r = 1 - \frac{v_z}{d_o}, \quad (1)$$

where v_z is the largest void dimension along the z coordinate and d_o is the initial void diameter. Note that vc_r is 1.0 when total void closure is reached.

RESULTS AND DISCUSSION

Results are reported and discussed in terms of top die stroke and press load at the time of complete void closure. Table 2 summarizes the results.

Table 2 - Results of simulations.

Die geometry	**Void position**	**Top die stroke (mm)**	**Press load (ton)**	**Void closure ratio (vc_r)**
Plate	Upper	720	1590	1
Dished		720	1600	1
Swage		820	1950	1
Plate	Lower	1000	1910	0.95
Dished		1000	2260	1
Swage		940	2160	1

For the upper positioned void, results were similar to plate die and dished die: top die stroke was the same and press loads were very close. This result occurred because the sidewall of the dished die did not contact the ingot; therefore, it worked like a plate die until the void closure. This result can be confirmed in Figure 5. Note that the ingot effective strain was equal for both die geometries.

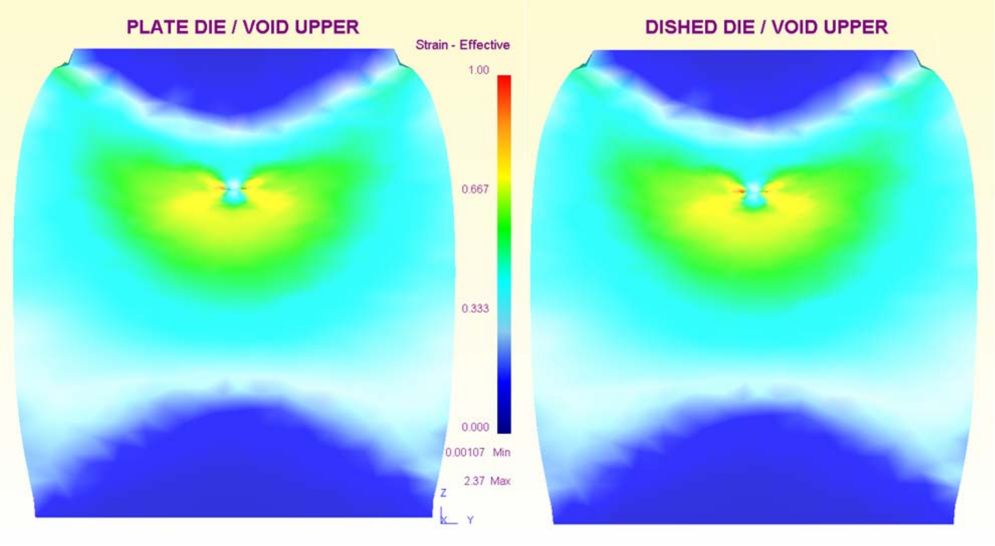

Figure 5 - Effective strain distribution for plate and dished die simulation.

The swage die simulation shows that this die geometry is not recommended since void closure took place with more top die stroke and press load.

With a lower void, it was noted that it is more difficult to close the void. For example, the plate die simulation did not close the void completely even for the total top die stroke. The void closure ratio vc_r calculated was 0.95. In the dished die simulation, the void was closed in the last step. Only the swage die simulation reached total void closure with more assurance. It can be concluded that for ingots with voids lower positioned, swage die was more efficient for complete closure void.

Dudra et al$^{(4)}$ concluded in their study that effective strain is a good indicator of void closure. Hence, this conclusion was used to improve the results of this work, considering that the effective strain is correlated with void closure. The quality of closure is measured in terms of the equivalent effective strain in the void position when the simulation is carried out with ingots free of voids. The effective strain estimation is accomplished by effective strain comparison between both ingots. Effective strain is extracted by the DEFORM 3D tool "*state variable between two points*". Figure 6 illustrates how this tool works.

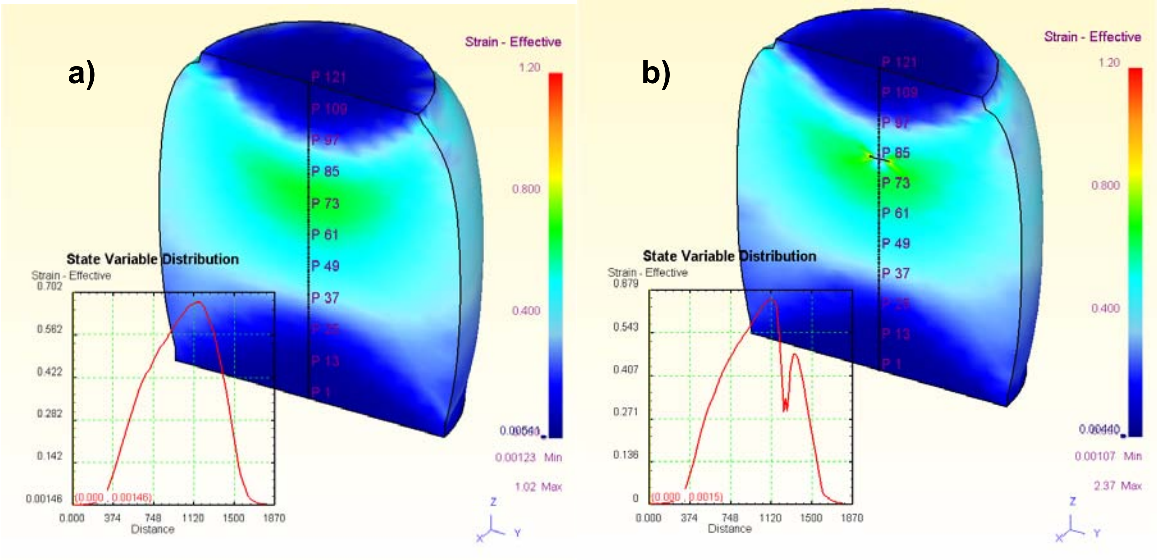

Figure 6 - Effective strain distribution along ingot centerline for plate dies.

To facilitate visualization, effective strain curves were overlapped, as shown in Figure 7 for plate die with void upper positioned.

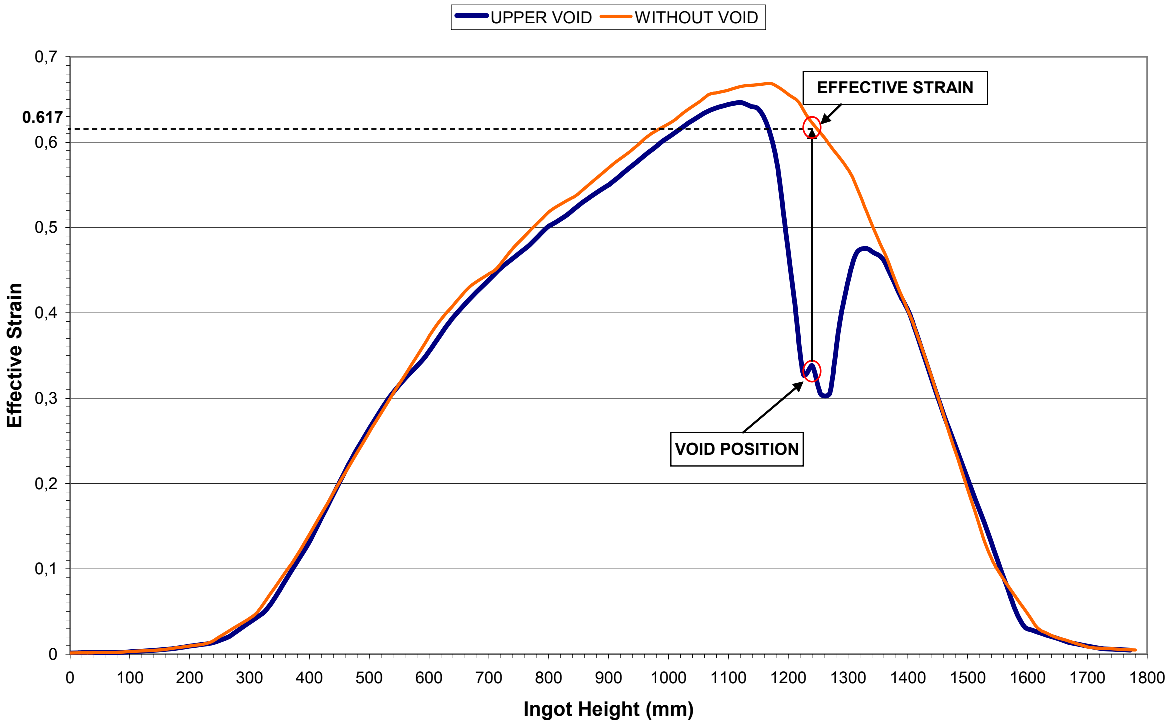

Figure 7 –Effective strain at upper void closure moment in plate die.

Table 3 contains the values of effective strain obtained in simulations with void closure.

Table 3 - Effective strain at void position.

	Plate die	Dished die	Swage die
Upper void	0.617	0.625	0.622
Lower void	-	0.667	0.671

It can be observed that the plate die simulation with lower void did not result in complete void closure, although the corresponding void closure strain was 0.636 at the last simulation step.

It is interesting to correlate void closure to the values of effective strain. For voids upper positioned this value is approximately 0.62 for the three different die geometries. With lower voids this value is 0.67 for the dished and swage die. Probably, if the effective strain for the plate die reached 0.67, it would have resulted in complete void closure.

Selection of the best die geometry for void closure depends on the void localization, since each die geometry deforms a specific region more intensely. Thus, it is necessary to make the region with large deformation coincident with the void position. Figure 8 shows where plate and swage die promoted more deformation.

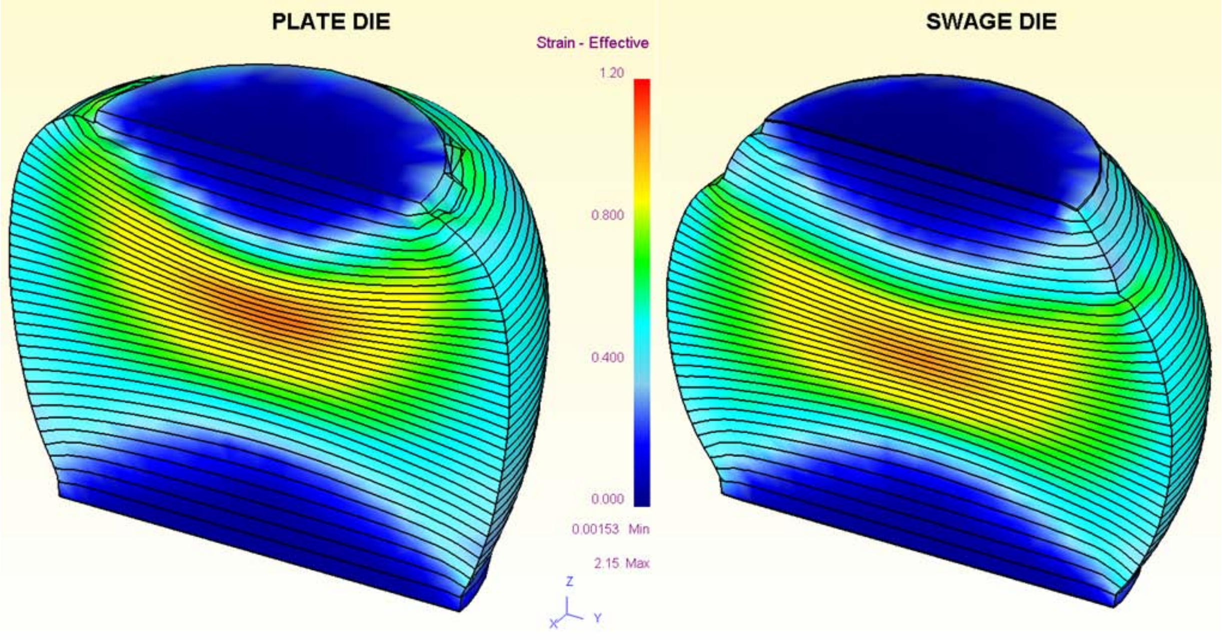

Figure 8 – Effective strain with flow lines at plate and swage die simulation without void.

The plate die promoted more deformation and displacement at the upper ingot half, while swage die produced displacement at the ingot center region. Another important factor to take into account is press load capacity. Simulation results showed that swage die required more press load than plate die. If there is press load limitation, then swage die would not be appropriate. Hence, it would be necessary to look for alternative die geometries or another forging technique to ensure void closure.

CONCLUSION

Void closure in large ingots by upsetting was successfully simulated through finite element simulation. It is observed that void closure depends on void position due to the influence of the region of frictional constraint metal flow. This region was created on account of the friction between ingot and dies. This region remains undeformed or presented small deformations, what explains why the void positioned lower was difficult to close completely.

There is no unique best die geometry for internal void closure by upsetting process. In the case where there is no limitation in the forging press load, swage die was the less efficient die geometry when void is upper localized. On other hand, for voids lower positioned, swage die was the most efficient die geometry.

Another important issue to observe is the correlation between effective strain and void closure. It was noted that the corresponding effective strains for void closure at the same position were close, irrespective of die geometry. It is suggested to continue this study in future, in order to understand the mechanism of void closure with other forging strategies. Moreover, it would be interesting to investigate large ingot solidification processes by numerical simulation in order to obtain more accurate information about void geometry and position.

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