Abstract
Numerical simulation and physical modeling performed on small-scale ingots made from pure lead, having a hole drilled through their centerline to mimic porosity, are utilized to characterize the deformation mechanics of a single open die forging compression stage and to identify the influence of the lower V-die angle on porosity closure and forging load requirements of large cast ingots. Results show that a lower V-die angle of 120° provides the best closure of centerline porosity without demanding the highest forging loads or developing unreasonably asymmetric shapes that may create difficulties in multi-stage open die forging procedures.

Keywords
Open die forging, V-shaped die, porosity closure, physical modeling, numerical simulation

Introduction
Open die forging involves the shaping of metallic ingots between an upper die attached to a vertical ram and a lower die attached to an anvil or a press bed. Most open die forgings are performed on flat dies but in case of shafts utilized in ships, power plants or wind turbines, which are compressed from large ingots above the recrystallization temperature, it is recommended to utilize multi-stage open die forging in conjunction with lower V-dies. Rotation of the ingots between each forging stage is necessary to progressively shape the raw material into the desired configuration and to ensure that the entire raw material undergoes plastic deformation. Figure 1 shows a photograph of the open die forging of a shaft made from a large cast ingot.

Because open die forging does not confine or restrain the raw material in the dies, it poses the challenge of producing custom-designed large size components from ingots with hundreds of tons in weight and worth hundreds of thousands to millions of euros, in a number of compression stages while preventing internal porosity to grow into critical defects. Internal porosity is more pronounced at the centerline of the ingots (specially towards its top) and is originated by improper feeding, slag inclusions due to impurities in the melt and segregations or coarse microstructure due to the long cooling time during the production process of large ingots by casting.

The aforementioned challenge was originally encompassed by Nasmyth who proposed the utilization of lower V-dies to render the “production of absolutely sound, solid wrought iron shafts, of whatever magnitude, equally easy as certain”. In his read before the Mechanical Section of the British Association, Nasmyth claimed that best results were obtained with an angle of 80° and argued that lower V-dies also allow “the free passage, or exit (towards the apex of the V-die), which is at all times preserved for the escape of the scales and impurities which fall from the hot iron during the process of hammering”.

The slip-line field analysis of plane-strain indentation of a thick slab by two opposing indenters performed by Johnson, more than one century after the practical design solution proposed by Nasmyth, allowed understanding the deformation mechanics of open die forging of large ingots between flat and V-dies. In concrete terms, Johnson proved the occurrence of tensile hydrostatic stresses that may stimulate
centerline porosity to evolve into critical forging defects, during compression of ingots between flat dies with a ratio \( H/L > 2 \) of the diameter \( H \) to the upper and lower lengths \( L \) of the contacting surfaces. This result allowed understanding the inadequacy of flat compression dies to redistribute segregations and to heal internal porosities originating from the casting process.

From Johnson\(^2\) until today there were many publications in open die forging technology, machine tools and calculation procedures based on analytical or numerical methods. Analytical methods such as the slip-line, slab and upper bound methods have been mainly utilized to estimate the compression load under simplified assumptions of geometry and material flow in order to keep the overall mathematical treatment at a fairly easy level. Numerical simulation based on the finite element method is capable of providing estimates of the compression loads and identifying safe and unsafe workability regimes under real operating conditions of material data, temperature, die and billet geometries, number of passes and rotation per pass, among others. An excellent review of the state-of-the-art in the field is provided in the ASM handbook on bulk forming.\(^3\)

Considering the long timeline of research in open die forging, it is surprising to note the lack of systematic investigations on the influence of the lower V-die angle on porosity closure and compression load of large cast ingots. This is attributed to the previously mentioned problem of manufacturing real size ingots using several different forging procedures and halving them lengthwise for subsequent investigation of porosity closure being above common research budgets. Among the few existing research publications in the subject, emphasis must be given to Stählerberg et al.,\(^4\) Keife and Stählerberg,\(^5\) and Dudra and Im.\(^6\) The first two publications are related and comprised fundamental research into the closure of artificial square voids by means of upper bound analysis and physical modeling with wax. The work was performed with rectangular cross sectional specimens compressed between flat frictionless platens and provided the first analytical estimates of the reduction\(^4\) and pressure\(^5\) that are necessary for the closure of voids under assumptions of rigid perfectly plastic flow and plane strain conditions. Results showed that void closure is more favourable under large reductions, which in practical terms would require heavy compression of the ingots before being turned through 90° for further deformation. This conclusion goes against current industrial practice since it would result in undesirable asymmetric shapes that would create difficulties in subsequent compression stages.

The work of Dudra and Im\(^6\) made use of numerical simulation and physical modeling with plasticine specimens. The specimens had an artificial internal hole to show that the geometry of the lower V-die has a significant influence on the deformation pattern and centerline porosity of large ingots produced by casting. However, the work was inconclusive regarding the influence of the lower V-die angles on porosity closure and compression loads, because the overall investigation was limited to flat dies and V-dies with an angle of 135°.

Zhang et al.\(^7\) presented a comprehensive study of porosity closure performed with different porous plasticity models. By comparing the resulting models with a unit cell model they concluded that a critical effective strain of approximately 0.5 should be imposed in order to ensure closure of the initial porosities. However, neither the geometry of the die nor the forging sequences were addressed.

Kim et al.\(^8\) performed a combined numerical and physical modeling of ingot upsetting (a preliminary process to be performed before ingot forging). The purpose of ingot upsetting is to remove oxide scale from the casting process and to extrude a manipulator pin for handling the ingot in the subsequent forging operations. By manufacturing spherical porosities in downscaled lead model ingots and compressing them in similar downscaled tools they were able to model a 520 tons ingot being upset forged. Subsequently they also performed sideways compression of the model ingots using two different forging plans. They showed that the ratio of initial ingot diameter to manipulator pin diameter as well as subsequent forging plans influence the overall porosity closure. However they did not consider different tool designs.

Christiansen et al.\(^9\) performed finite element simulations of open die forging with V-dies using a Gurson–Tvergaard–Needleman coupled damage model\(^10\) and concluded that lower V-dies with 90° angle perform better than flat dies regarding porosity closure. However, the investigation also missed generalization to other V-die layouts. More recently, Christiansen et al.\(^11\) focused on the influence of V-dies on porosity closure during multi-stage open
die forging with rotation between each forging stage and concluded that best results are obtained with lower V-dies with 120°. However, the numerical work that supports the results and discussion was performed under plane strain assumptions and the overall assessment against experimental data was limited to force-displacement evolutions and basic geometric features of the holes.

The aims and scope of this paper are focused on the above-mentioned gap in knowledge concerning the influence of lower V-die angles on centerline porosity and forging load requirements. The presentation combines finite element simulation and physical modeling at room temperature and, contrary to current industrial practice where open die forging takes place in small bites while the ingot is rotated at small angles, reduction was performed in a single compression over its entire length. This was necessary to ensure that porosity closure is not influenced by the ratio of the bite to the length of the specimen and to allow measurement of the deformed holes without damaging the specimens.

The paper is organized in the following sections: “Experimentation” section describes mechanical characterization of the model material and the apparatus and work plan that were adopted in physical modeling with small-scale preforms and tools, section “Finite element analysis” gives a brief overview of the numerical simulation procedures that were used throughout the investigation, “Results and discussion” section presents and discusses the results on the influence of a wide range of lower V-die angles on deformation mechanics, porosity closure and compression load and conclusions follow in the last section.

**Experimentation**

**Mechanical materials characterization**

The model material applied in the investigation was pure lead. This material is commonly utilized in physical modeling of bulk metal forming processes due to its capability of reproducing plastic flow of conventional engineering materials such as the cast ingots at hot forging conditions by means of experimentation at room temperature with low strain rates. The stress–strain response of pure lead was determined by means of compression tests performed at room temperature on cylindrical specimens with 20 mm height and diameter. The tests were carried out on an INSTRON SATEC hydraulic testing machine with a cross-head velocity equal to 100 mm/min (1.7 mm/s) under an average strain rate approximately equal to \( \dot{\varepsilon}_{pl} = 0.15 \text{s}^{-1} \). The resulting stress–strain curve following Ludwik–Hollomon’s material model (Figure 2) is given as follows

\[
\sigma = 33.61 (\dot{\varepsilon}_{pl})^{0.27} \text{MPa}
\]

where \( \sigma \) is the flow stress and \( \dot{\varepsilon}_{pl} \) is the effective plastic strain.

**Methodology and work plan**

The investigation on porosity closure and compression load requirements in open die forging made use of cylindrical lead specimens, 100 mm long and 30 mm in diameter, and a lower V-die set machined from an aluminum AA6061-T6 block that is capable of providing four different experimental layouts corresponding to die angles of 60°, 90°, 120°, and 150°.
The compression between flat parallel dies (not shown in the figure) was taken as a reference test case for comparison with V-dies.

The total length to diameter ratio of the cylindrical specimens was $T_L/D = 3.33$ in order to approach as far as possible the plane strain deformation conditions ($T_L/D > 5$) while still being possible to drill centerline holes with 5 mm diameter in a single operation. The holes were drilled with the aim and objective of replicating centerline porosity of real industrial ingots produced by casting.

Fu et al.\textsuperscript{13} halved, lengthwise, one ingot of 100 tons utilized for manufacturing low pressure rotors for nuclear power plants in order to observe and quantify the size of the centreline porosity. They found that a zone along the centerline, approximately equal to 10\% of the ingot diameter in size contained severe porosities and concluded that billets could still be hot forged to give a sound final component. The centreline porosity ratio utilized in the present study is twice in size and, therefore, is not vastly disproportional to real size centreline porosities.

The decision of drilling centerline holes from one edge to the other instead of producing small voids homogeneously (or randomly) distributed in a cross section around the centerline of the specimens (like, for example, in case of Ståhlberg et al.\textsuperscript{4} and Keife and Ståhlberg\textsuperscript{5}) aims to account for the simultaneously influence of plane strain and plane stress plastic flow conditions on the influence of the lower V-die angle on porosity closure and load requirements. In fact, the dispersion of small voids in a single cross section does not replicate internal porosity of real ingots produced by casting, which is more pronounced at the centerline, and, therefore, physical modeling also fails in modeling porosity along their length, which naturally arises during the production process of large ingots by casting.

The cylindrical specimens were compressed 3 mm (Figure 3(b)) in the same hydraulic testing machine where the model material was characterized. Moreover, the experiments made use of a cross-head velocity of the upper die similar to that used in the compression tests. Figure 4 shows photographs of specimens after being deformed by means of different lower V-dies. The lower flat die is included for reference purposes.

The load–displacement curves were directly obtained from the load cell and displacement transducer available in the hydraulic testing machine.
whereas the morphology and area of the circular holes were characterized by means of a computer assisted scanning procedure developed by the authors.

After finishing compression, the specimen ends were optically scanned (Figure 5(a)) and the final hole area $A_{\text{final}}$ was determined by means of a computer program that performs the counting of pixels of the scanned images. The program was written in MATLAB and is based on the automatic recognition of groups of black pixels by summing the number of color values of the surrounding pixels around a given pixel. Whenever this number is sufficiently small (the color value for a black pixel has the value “0”), the pixel is considered to be part of a black region (Figure 5(b)). Since the scan resolution is known and the area of each pixel is also known, the hole area $A_{\text{final}}$ is determined by multiplying the number of pixels constituting the deformed hole by the area of each pixel. Regarding Figure 5, it is worth noting that the drawn pixel grid size available in the figure is much larger than that utilized in the investigation because the purpose of the figure is solely to illustrate the explanation of the methodology utilized in the automatic identification of hole features from scanned images.

**Finite element analysis**

**Formulation**

Because open die forging experiments were carried out at room temperature with a very small cross-head velocity, no inertia effects were found and, therefore, no dynamic contributions to plastic flow needed to be taken into consideration. Such conditions allowed numerical modeling of the experiments to be performed with the finite element flow formulation, which is based on the following weak variational form

$$
\int_V \sigma \delta \varepsilon \mathrm{d}V + K \int_V \varepsilon^{pl} \delta \varepsilon \mathrm{d}V - \int_{S_i} F_i \delta u \mathrm{d}S = 0
$$

where $V$ is the control volume limited by the surfaces $S_v$ and $S_i$, where velocities $u_i$ and tractions $F_i$ are prescribed, $\sigma$ is the effective stress, $\varepsilon^{pl}$ is the effective plastic strain rate and $K$ is a large constant imposing the incompressibility requirements of the plastic deformation of metals.

The finite element simulations included in this paper made use of two- and three-dimensional computer programs that were developed by the authors. Details on computer implementation regarding the discretization of the weak variational form by finite elements, selective integration procedures by means of complete and reduced Gauss-point integration schemes and material self-contact and contact with tooling, among other topics, are comprehensively discussed in Nielsen et al.\textsuperscript{14}

**Numerical simulation**

Three-dimensional finite element computer models were set-up for the numerical simulation of open die forging. The cylindrical lead specimens were discretized by means of structured meshes of hexahedral elements and the upper flat and lower dies were discretized by means of contact-friction linear triangular elements. Figure 6, for example, shows the preform before and after being compressed in open die forging using a lower V-die with an angle of 90°.

The choice of hexahedral elements instead of tetrahedral elements as it is commonly available in commercial three-dimensional finite element computer programs for metal forming is justified by the fact that meshes based on tetrahedral result in larger models (and, therefore, in larger computational requirements) than meshes based on hexahedra for the same level of accuracy. Moreover, tetrahedral cause critical errors when distorted, whereas hexahedra have better behavior even when distorted.\textsuperscript{15}

The numerical simulations were performed through a succession of displacement increments each of one modeling approximately 1% of the initial
diameter of the specimens. No remeshing operations were performed and the overall computing time for a typical analysis containing 12,000 elements and 14,000 nodal points was below 3 h on a computer equipped with two Intel Xeon X5690 3.46 GHz processors and making use of 8 cores.

Two-dimensional plane strain and plane stress finite element computer models were specifically setup to evaluate closure of the centerline hole. These models were built upon previous results by Christiansen et al.,\textsuperscript{11} who proved plane strain to be a reasonable assumption for the plastic deformation of cylindrical specimens with a total length to diameter ratio $L/D = 3.33$ for reductions up to approximately 15%. The above-mentioned work also showed plane stress to be closer to the actual state of stress at the edges where the outward pointing normal stress is zero.

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The two-dimensional finite element models made use of a much more refined discretization of the initial cross section of the specimens, consisting of approximately 700 elements, and offered the advantage of providing numerical estimates in less than 1 min using a standard laptop computer equipped with an Intel i7 CPU (2.7 GHz) processor and making use of a single core.

A summary of the main experimental settings and simulation parameters is included in Table 1. The friction factor was estimated by fitting the predicted force-stroke curves to the experimental ones.

### Results and discussion

**Deformation mechanics**

Figure 7 shows the finite element predicted distribution of the hydrostatic stress at the end of stroke for two cylindrical specimens that were forged using a lower V-die with 90° and a reference flat die.

As seen in the figure the distribution of hydrostatic stress presents a variation from the central region (undergoing plane strain conditions) to the edges of the specimens (undergoing plane stress conditions) and is globally more compressive in case of the specimen that was forged using a V-die with 90°. The three compression regions (refer to “A” and “B” in Figure 7(a) and notice that “C” is not shown in the figure because it is located opposite to “B”) that result from open die forging using a lower V-die are different and easily distinguished from the two opposed compression regions that are generated when using a lower flat die (refer to “A” and “B” in Figure 7(b)). The influence of the number and location of these compressive regions on the overall morphology of the centerline hole is also clear. In fact, the three compressive regions originating from the lower V-die with 90° ensure a better closure of the centerline hole than the two compressive regions that are originated by the lower flat reference die.

However, the influence of the lower V-die geometry on the closure of the centerline hole will be analyzed in more detail by means of two-dimensional finite element models that are capable of replicating the limiting plastic deformation conditions corresponding to plane strain and plane stress. The result of this analysis is provided in the following section.

### Center hole

Measurement of the holes that were drilled along the centerline of the specimens to mimic porosity of large casted ingots provided an average value of the initial
area $A_{\text{initial}} = 18.25 \text{ mm}^2 \ (\phi \ 4.82 \text{ mm})$ with a standard deviation $\sigma = 2.1 \text{ mm}^2$. The area of the center holes at the end of stroke was determined by means of the computed assisted pixel counting procedure that was previously described in section “Methodology and work plan” and the results are shown in Figure 8.

The experimental and finite element data included in Figure 8 were normalized by the ratio of the final to the initial diameter of the hole: $A_{\text{ratio}} = A_{\text{final}} / A_{\text{initial}}$ and, as mentioned before, the models were set-up to replicate limiting plastic deformation conditions of plane stress and plane strain. The finite element models also made use of two different initial hole diameters (4.5 mm and 5 mm) in order to account for the uncertainty of the initial morphology of the holes resulting from the drilling operation.

As shown in Figure 8, the experimental results of $A_{\text{ratio}}$ fall in-between the finite element computed estimates produced by plane stress and plane strain models, without a clear trend of being closer to one of them. This may be attributed to the total length to diameter ratio of the cylindrical specimens ($T_r / D = 3.33$) being somewhat below $T_r / D = 5$, normally required for assuming plane strain deformation conditions. Still, the overall conclusion resulting from both finite element models is that hole closure is more effective when the lower V-die angle varies between 120° (for plane strain conditions) and 130° (for plane stress conditions).

This conclusion is in good agreement with the experimental measurements of hole closure that are also provided in Figure 8.

**Forging load**

Figure 9 presents a comparison between the experimental and finite element predicted loads in case of open die forging using a flat reference die. As seen in the figure, the numerical predictions obtained by means of three-dimensional models match the experimental results while those provided by two-dimensional plane strain and plane stress models slightly overestimate and underestimate the experimental values, respectively. Such differences are mainly attributed to the inability of two-dimensional models to replicate material flow at the edges of the specimens and to properly account for the distribution of pressure along the overall length of the test specimens.

The above-mentioned disagreement between two-dimensional modeling and experiments is more pronounced under plane stress assumptions because the compression of the specimens is closer to plane strain conditions. This fact also explains the reason why
plane stress models will not be considered in the analysis of the forging load despite their interest in the analysis of the morphology of the holes located at the edges of the specimens.

The generalization of the experimental and finite element predicted evolutions of the load-displacement curves for a wide range of lower V-die angles ranging from 60° to 180° allowed determining the maximum forging loads as a function of the lower V-die angles (Figure 10). The estimates provided by means of three-dimensional models made use of an average initial hole diameter of 4.75 mm whereas the values given by two-dimensional plane strain models made use of initial hole diameters of 4.5 mm and 5 mm diameter in

![Figure 8](image1.png)

**Figure 8.** Experimental and finite element predicted values of the ratio of the final to the initial diameter of the hole: $A_{\text{ratio}} = A_{\text{final}}/A_{\text{initial}}$ as a function of the angle of the lower V-die.

![Figure 9](image2.png)

**Figure 9.** Experimental and finite element predicted evolution of the load–displacement curve in case of open die forging using a lower flat reference die.
order to account for the uncertainty of the initial morphology of the holes resulting from the drilling operation.

The overall agreement between experimental and numerical estimates of the maximum forging load is good and confirms peak values to occur for lower V-die angles close to 90°. Because the maximum forging load requirements are attained for a lower V-die angle (90°) that is different from that ensuring the most effective closure of the centerline hole (120° to 130°), it is possible to conclude, on contrary to pre-conceived notions and ideas about the deformation mechanics of open die forging, that the maximum load requirements do not ensure the most effective closure of the centerline holes. This conclusion is of major relevance to industrial companies performing open die forging with large ingots produced by casting because understanding that the best porosity closure is obtained with a maximum load requirement 15% below the ultimate maximum load requirement of the process will easily account for saving hundreds of tons in the forging load requirements.

**Conclusions**

The design of the lower V-dies utilized in open die forging play a significant role regarding the maximum load requirements and on internal porosity closure of large ingots produced by casting. Physical modeling using cylindrical specimens made from pure lead with a drilled centerline hole and numerical simulations performed with two and three-dimensional models revealed that best closure of porosity does not occur for the lower V-die angle requiring the maximum forging load. In fact, best results are obtained for lower V-die angles of approximately 120° to 130° and correspond to a reduction of nearly 15% of the maximum load required by a lower V-die with an angle of 90°.

Good performance of two-dimensional plane strain finite element models in predicting the overall deformation mechanics of the process with minor computation time requirements opens the possibility of applying these models in dedicated computer programs available at the shop-floor for helping engineers and technicians to take real-time decisions on the amount of stroke to be used in each forging pass, the total number of forging passes and the forging sequence, among others. This is currently not feasible with three-dimensional models that still rely on high hardware and computational time requirements.

**Conflict of interest**

None declared.

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