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ANALYSIS OF INGOT FORGING DAMAGE EVOLUTION USING DIFFERENT SIMULATION METHODS

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Summary

Various examples on optimization of the ingot forging process are presented. Physical as well as numerical simulation using FE is adopted. It is shown that the choice of damage model in the numerical simulations may influence the conclusions drawn.

1. Introduction

Large metallic components like shafts for power plant turbines or ships' propulsion are manufactured by forging of an ingot cast in steel. The casting process usually gives rise to a number of defects in the ingot e.g. porosities due to improper feeding or gas formation, segregations or coarse microstructure due to long cooling time. These defects can, to some extent, be remedied by subsequent hot forging, thus ensuring a sound, final product.

Ingot forging and die layout are mostly based on accumulated knowledge gained through practical experience. Normally, the ingot is forged in a hydraulic press using a flat upper die and a V-shaped lower die (**Fig.1**).

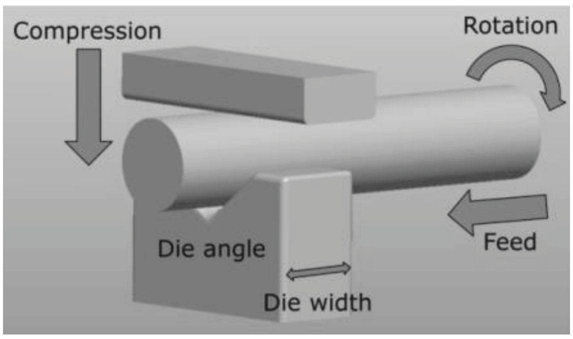

Fig.1 Schematic representation of the ingot forging process

After compression, the upper die is removed, the ingot is lifted from the lower die and rotated a specific amount around its centre axis, after which it is again placed in the V-groove and compressed by the upper die. This procedure is continued until the cross-section is sufficiently deformed. Then the ingot is displaced by axial feeding in-between the dies and a new cross-section is forged. By practical experience, Nasmyth [1] has noticed that forging using a V-shaped lower die improved the internal soundness of the forged ingot. He estimated the optimum die angle to be around 80^{o}. Slipline field analysis by Johnson [2] provides theoretical insight regarding the deformation mechanics of the process and confirms the superiority of V-shaped lower die geometries against the flat lower die.

Investigations on defects in ingot forging are constrained by the technical impracticability of performing full-scale experiments due to the overall size, load requirements and cost of the ingots. The alternative is to acquire fundamental knowledge by means of small-scale, physical modelling or finite element analysis.

The aim and scope of this paper is to present examples of various methods of analysis for investigating and optimizing the ingot forging process, especially regarding determination of optimum lower die angle, which results in minimum centreline defects.

2. Physical modelling experiments

Downscaled lead billets were manufactured by casting billets in commercially, pure lead and subsequently machining them to 100mm in length and Ø30mm in diameter. Centreline Ø5mm holes were drilled through the billets in order to mimic centreline porosity defects appearing in full-size ingots. Different lower die angles of 60°, 90°, 120° and 150° were machined in an AA6061-T6 block, which allowed compression of the entire length of the lead billets by a number of different lower die angles and a plane upper die. A press stroke of 3mm was applied.

Compression of the lead billets was modelled numerically using an in-house developed 2D finite element code in order to compare experiments with modelling. The stress-strain curve of the workpiece material was determined by uniaxial compression test. Fitting to a Hollomon hardening law gave the following: $\sigma_o = 33.6\bar{\varepsilon}^{0.27} MPa$, where σ_o is the flow stress and $\bar{\varepsilon}$ the effective strain. Dies were prescribed as rigid and tool-workpiece friction by the constant friction model $\tau = m_f k$, where τ is the frictional shear stress, $m_f = 0.1$ is the friction factor and k is the flow stress in pure shear.

Closure of the drilled centreline holes was evaluated quantitatively by optical scanning of the billet ends measuring the cross-sectional area of the drilled holes after compression by means of an in-house developed pixel recognition program. The area ratio $A_{final}/A_{initial}$, where $A_{initial}$ and A_{final} are the initial and final cross-sectional areas of the drilled centreline hole, is used as a measure of the efficiency in closing the centreline hole.

A comparison of experiments with FE-simulation can be seen in **Fig.2**.

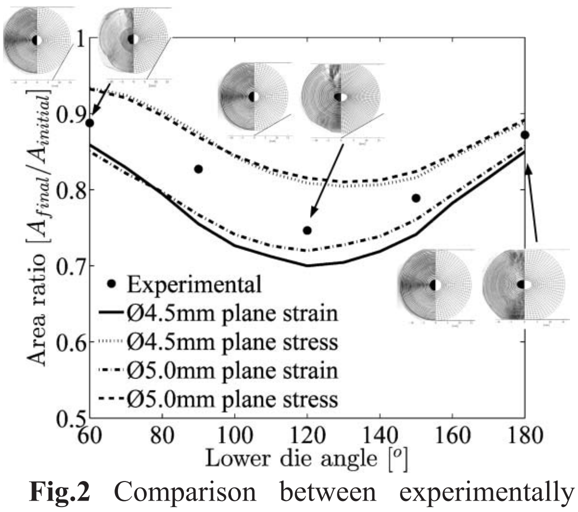

Fig.2 Comparison between experimentally and numerically determined centreline hole closure versus lower die angle. Selected scans of lead billets before and after compression are shown in comparison with FE predictions.

Due to some variation in the measured, initial size of the centreline holes, both compression of initial Ø4.5mm and Ø5mm holes were simulated. Both plane stress and plane strain deformation was simulated. It is noticed from **Fig.2** that the lower die angle has significant influence on the degree of centreline hole closure and that the experimentally measured degree of closure follows the trend indicated by the FE-simulations. A distinct optimum in hole closure is observed around a lower die angle of 120-125°. The difference in initial hole size is of less importance than whether plane stress or plane strain is assumed. For a further description of the experiments and the FE-analysis, refer to Christiansen et al. [3].

3. Influence of material hardening

In the following it is investigated, whether the optimum lower die angle is influenced by the material properties, especially the influence of strain and strain rate hardening. Since the ingot cools off during the hot forging operation, it may be necessary to change the die during the forging process, if the optimum lower die angle is changing due to changes in hardening properties. In order to investigate this forging of ingots with a centreline hole and different material hardening behaviors, different single compression forging operations are analyzed using the in-house developed 2D FE code. The centreline hole is chosen as 10% of the ingot diameter, which is 2000mm, similar to a real, full size ingot. With a typical die width in a real production of 1000mm, the ratio of die width to ingot diameter is 0.5, hence plane stress may be assumed in the ingot cross-section during compression. A 200mm stroke of the upper die is applied. These parameter values are similar to industrial practice. The centreline hole closure is evaluated by the area ratio.

Three different hardening models are investigated; Hollomon hardening ($\sigma_o = C_1\bar{\varepsilon}^{n_1}$), Norton hardening ($\sigma_o = C_2\dot{\bar{\varepsilon}}^{m_2}$) and Fields-Backofen hardening ($\sigma_o = C_3\bar{\varepsilon}^{n_3}\dot{\bar{\varepsilon}}^{m_3}$).

A plot of the area ratio versus the lower die angle with the material hardening model as parameter can be seen in **Fig.3**.

It is seen that although the degree of centreline defect closure depends on the material model, the optimum lower die angle appears to be rather constant, equal to 130°-140°, no matter which material model is adopted. It is furthermore noticed that the friction factor m_f has a minor influence on the optimum lower die angle.

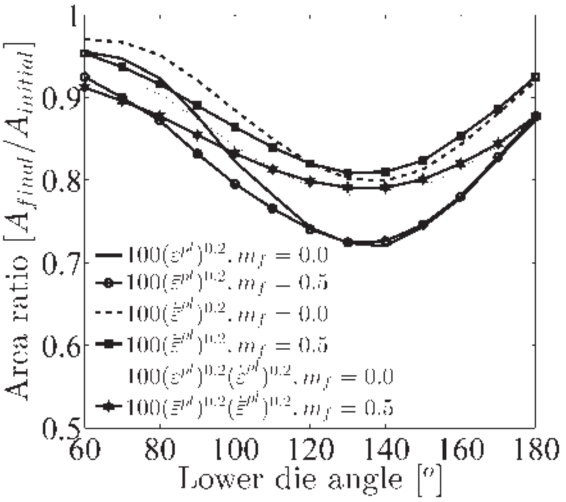

Fig.3 Area ratio, after single stroke compression of ingots with centreline defect, as function of lower die angle, material hardening and friction factor.

For further information regarding modelling and optimization of the lower die angle with respect to material hardening refer to Christiansen et al. [4].

4. Modelling of damage

Due to the increase in computer power, it has now become feasible to model the entire ingot forging process numerically. As a result an increasing interest from both scientific and industrial point of view appears to combine casting simulations, predicting e.g. porosity distribution in the ingot after casting, with forging simulations to determine, whether the porosities are being closed.

A full 3D simulation of an ingot forging process is performed. The ingot is 2000mm in diameter and 4000mm long. Dies are 1000mm in width and the lower die angle is 120°, parameter values, which are comparable to industrial practice. Forging with a flat lower die is, furthermore, analyzed for reference. The ingot cross-section is compressed 16 times each time with 200mm stroke length and 45° intermediate rotation between strokes. An axial feed of 400mm is applied, which is close to the maximum value recommended to ensure a sound centreline region after forging [5]. Furthermore, an excessive feed of 800mm is analyzed for comparison. The ingot has a prescribed porosity distribution varying radially as schematically shown in **Fig.4**.

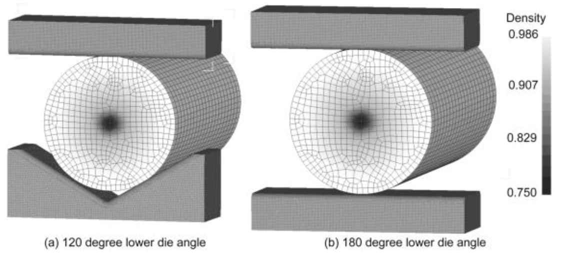

Fig.4 Simulation layout for forging a full size ingot using (a) a 120° lower die and (b) a 180° lower die

The relative density is defined as $R = \rho/\rho_o$ where ρ is the density in a porous element and ρ_o is the density of the fully dense material. In the centre section of a diameter 200mm $R = 0.75$, after which a linear increase in R to 0.9 appears at a diameter of 400mm. After that the relative density is assumed to increase linearly to 1.0 at the outer surface of the ingot. As an idealization, there is assumed to be no variation in the relative density in the length direction of the ingot.

Suppression or formation of damage is modelled by the Shima-Oyane porous plasticity model [6] and the normalized Cockcroft & Latham criterion [7]. For the Shima-Oyane porous plasticity model, damage can decrease if the evolution in relative density $\dot{R}$ is negative:

$$\dot{R} = -\dot{\varepsilon}_v R \qquad (1)$$

where $\dot{\varepsilon}_v = \dot{\varepsilon}_{kk}$ is the volumetric plastic strain rate. The Cockcroft & Latham criterion is given by:

$$D = \int \frac{\sigma_1}{\bar{\sigma}} d\bar{\varepsilon} \qquad (2)$$

where σ_1 is the largest principal stress, $\bar{\sigma}$ is the effective stress, $d\bar{\varepsilon}$ is the effective plastic strain increment and D is the accumulated damage value. Damage is not allowed to decrease in the FE implementation.

Fig.5 and **Fig.6** show the calculated relative density and ductile damage respectively. It is noticed that different conclusions may be reached regarding the influence of die layout and forging procedure on damage, depending on which model for damage evolution that is used. When applying the porous plasticity model as damage model (**Fig.5**), all simulation layouts result in a sound ingot after forging. This is in contradiction to current knowledge regarding ingot forging, where a lower die angle of 120^o is known to be superior to 180^o. If damage prediction is based on the normalized Cockcroft & Latham criterion (eq. (1)), the largest damage is predicted for the 180^o lower die and the smallest damage is predicted for the 120^o lower die in agreement with current knowledge and industrial practice. For both damage criteria feed size seems to be of less importance to the evolution of ductile damage.

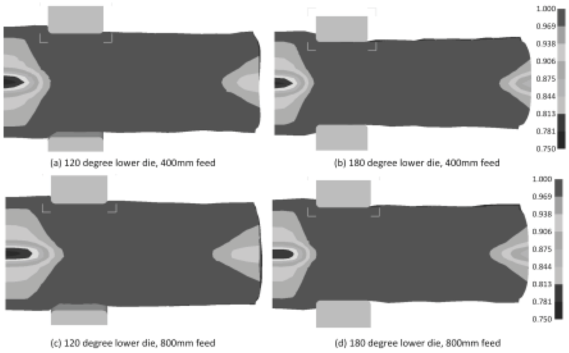

Fig.5 Relative density after forging an ingot cross section. (a)-(d) show different values of lower die angles and feed sizes

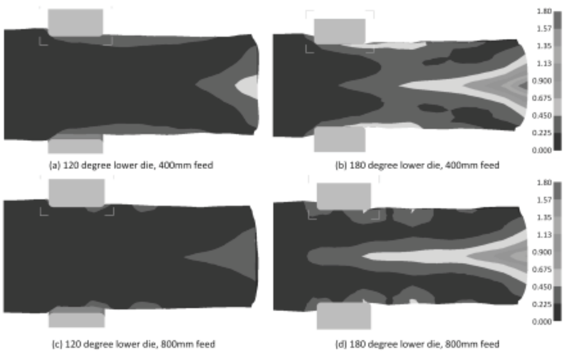

Fig.6 Ductile damage after forging an ingot cross section. (a)-(d) show different values of lower die angles and feed sizes

For further information and results regarding damage modelling in ingot forging, the reader is referred to Christiansen et al. [8].

5. Conclusion

Various examples of both physical and numerical optimization of the lower die angle in ingot forging have been presented.

It was found that physically downscaled model ingots can be used as substitutes for real ingots, thus enabling physical experimentation under laboratory conditions.

2D FE simulations have been applied for optimization of the lower die angle regarding ingot material hardening properties. It was found that the optimum lower die angle is independent of ingot material hardening behaviour.

Full 3D FE simulations of the ingot forging process was also performed for a limited number of lower die angles and feed sizes. It was shown that care should be taken when selecting the model for evaluating ductile damage evolution in hot forging.

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