Numerical optimization of die geometry in open die forging

Christiansen, Peter; Hattel, Jesper Henri; Bay, Niels Oluf; Martins, Paulo A.F.

Published in:
Proceedings of International Conference on Advanced Manufacturing Engineering and Technologies (NEWTECH 2013)

Publication date:
2013

Numerical optimization of die geometry in open die forging

Peter Christiansen[1], Jesper H. Hattel[1], Niels Bay[1], Paulo A.F. Martins[2]

[1]Department of Mechanical Engineering, Technical University of Denmark, DTU – Building 425, DK-2800 Kgs. Lyngby, Denmark,
[2]Instituto Superior Tecnico, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
petc@mek.dtu.dk

ABSTRACT

This paper deals with numerical optimization of open die forging of large metallic ingots made by casting implying risk of defects, e.g. central pores. Different material hardening properties and die geometries are combined in order to investigate, which geometry gives rise to maximum closure of a centreline hole in a single compression operation. Friction is also taken into account.

The numerical analysis indicates that a lower die angle of approximately 140^o results in the largest centreline hole closure for a wide range of material hardening. The value of optimum die angle is not influenced by friction, which was found only to change the degree of centreline porosity closure in case of small lower die angle.

KEYWORDS: Ingot forging, Centreline porosity closure, Numerical simulation, Die design

1. INTRODUCTION

The open die forging process is applied for production of large metallic parts such as shafts for ship's propellers, power plant turbines or wind turbines. It is important to ensure the mechanical soundness of the shafts, since failure of such components is expensive and unacceptable.

Manufacturing large shafts consists of a number of operations: First a large steel block (known as an ingot) is cast. After solidification and cooling, the cast ingot is reheated to approximately 1200^{o}C and subsequently hot forged. The forged ingot is then left to cool down after which it is machined by turning to its final shape. The machined workpiece is then hardened and grinded.

The open die forging process is schematically illustrated in Fig. 1. The ingot is placed in-between a flat upper die and a V-shaped lower die, after which the upper die is moved downwards to compress the ingot. After compression, the ingot is lifted from the lower die and rotated around its centre axis (usually 45^o) and the compression operation is repeated.

Repetition is carried out a number of times to finish a cross-section of the ingot, after which the ingot is moved forward and a new cross-section is forged.

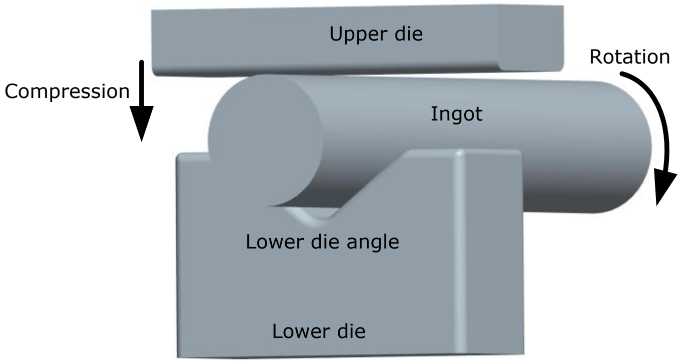


Fig. 1. Schematic view of the open die forging process.

According to ASM Handbook [1] the main reason for performing the open die hot forging is to minimize defects originating from the casting process. Such defects are for instance segregations, inclusions, porosities due to gas entrapment or poor feeding, or coarse grain structure due to long cooling time. The centreline of the ingot is where these defects are most pronounced. This is because the centreline of the ingot is the last place to solidify. It is possible to diminish and sometimes even remove these defects by hot forging: recrystallization may be triggered by the plastic deformation, inclusions can be crushed to smaller particles and porosities may be closed during forging. The latter is the scope of the present investigation.

Pioneering investigation of the open die forging process was conducted by Nasmyth [1]. Based on practical experience he found that a V-shaped lower die was superior to a flat lower die regarding closure of centreline porosities and to ensure soundness of the final product.

A theoretical analysis of the open die forging process using V-shaped and flat dies was presented by Johnson [2], who applied slipline analysis for die compression of circular cylindrical ingots. Despite the need to assume ideal-plastic materials and plane strain deformation, slipline analysis improved the understanding of why utilization of two plane dies resulted in hydrostatic tension, hence opening of porosities, at the centre of the workpiece during forging.

Upper bound analysis of compression of cylindrical billets with square cross section containing porosities was presented in Keife & Ståhlberg [3] and corresponding model wax experiments in Ståhlberg et al. [4]. Although providing a better understanding of why porosities close during plastic deformation, the analysis is based on plane strain assumption and rigid-plastic materials. The porosities are furthermore equally distributed across the specimen analysed, thereby only approximately resembling the porosity distribution in a cast ingot, where porosity density increases towards the centre of the ingot.

Dudra & Im [5] carried out plane strain numerical simulation of open die forging of model ingots with a centreline hole to mimic a porosity using a pair of plane and a pair of V-shaped 135^{o} dies. They confirmed the aforementioned work of Nasmyth and Johnson that V-shaped dies are superior to plane dies regarding closure of centreline porosities.

A numerical study using the Gurson-Tvergaard-Needleman porous plasticity model was presented in Christiansen et al. [6]. A real size ingot with a porous centre region was compressed in a number of forging steps using a flat and a 90^{o} V-shaped lower die. It was found that the flat lower die resulted in hydrostatic tension at the centre of the ingot while the V-shaped die was able to supress the hydrostatic tension hereby preventing porosity increase at the centre of the ingot. However only these two lower die angles were investigated, hence there could be other die angles more suited for centreline porosity closure.

An experimental study by Christiansen et al. [7], where downscaled lead model ingots with drilled centreline holes to mimic centreline porosity were compressed using different lower die angles, indicated that different degrees of centreline porosity closure were achieved while applying the same length of press stroke. The study indicated an optimum lower die angle, where centreline porosity closure would be maximized. The study also showed good agreement between the numerical simulation and the physical modelling.

The scope of the present paper is to estimate, which lower die angle may be most suited for centreline porosity closure. The paper furthermore aims to investigate, whether this optimum lower die angle is affected by variations in strain or strain rate hardening. The change in mechanical behaviour, i.e. the stress response, may be due to ingots of different materials, thermally induced changes in hardening properties due heating to different initial temperature or cooling during deformation.

2. Numerical modelling

2.1. Finite element flow formulation

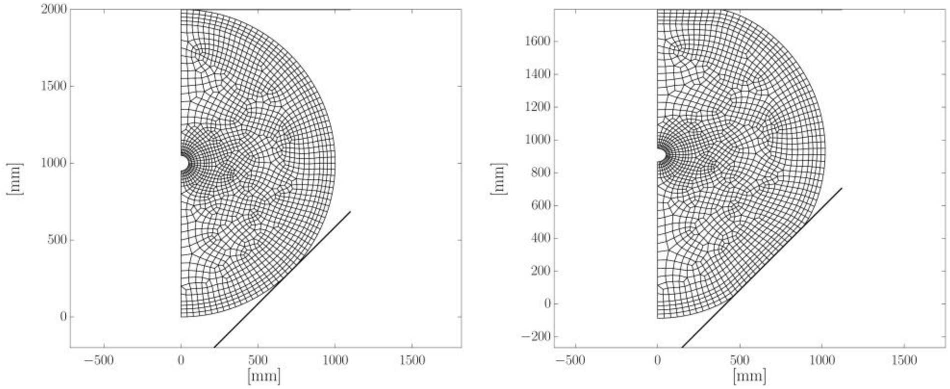
Since the open die forging of large ingots is normally performed by means of the relatively slow moving punch of a hydraulic press, accelerations are assumed to be insignificant and dynamic effects may be neglected. This allows the numerical modelling of the process to be carried out with the quasi-static finite element flow formulation, which is based on the following weak variational formulation:

$$\int_V \bar{\sigma}\delta\dot{\bar{\varepsilon}}^{pl} dV + K\int_V \dot{\varepsilon}_V^{pl}\delta\dot{\varepsilon}_V^{pl} dV = \int_S \tau_i \delta u_i dS \qquad (1)$$

where V is the control volume limited by surfaces S_u and S_f, where velocities u_i and tractions τ_i are prescribed, $\bar{\sigma}$ is the effective stress, $\dot{\bar{\varepsilon}}^{pl}$ is the effective plastic strain rate, K is a large constant penalizing volume shrinkage and hereby enforcing plastic incompressibility and $\dot{\varepsilon}_V^{pl} = \dot{\varepsilon}_{ii}^{pl}$ is the volumetric plastic strain rate. Friction is modelled using the constant friction model $\tau = m_f k$ where $0 \le m_f \le 1$ is the friction factor and k is the shear flow stress. Both full and reduced integration schemes are utilized when performing the numerical integration. Details on computer implementation of the flow formulation may be found in Nielsen et al. [8].

2.2. Simulation layout

The ingot investigated is considered to be 2000mm in diameter and having a centreline hole 100mm in diameter (5% of total diameter) in order to mimic a porous centre region. The ingot is placed between a flat upper die and a V-shaped lower die and compressed once 200mm, i.e. 10% of the ingot diameter. Lower die angles ranging from 60^o to 180^o (flat lower die) are employed. In order to reduce computational time only 2D models taking advantage of centreline symmetry are utilized. Discretization is performed by means of approximately 1700 quadrilateral elements. Plane stress loading conditions are assumed. This is a reasonable assumption if the ratio of die width w to ingot diameter d is reasonable small. In an industrial case of open die forging, an ingot with a diameter of approximately 2000mm was forged using a die with a width of 1000mm giving a ratio w/d = ½, hence plane stress is a relevant assumption for such a forging case. An example of mesh and simulation layout can be seen in Fig. 2.



(a) (b)

Fig. 2. Ingot before (a) and after (b) being forged by a 120^{o} lower die.

Two different friction scenarios are investigated: frictionless and constant friction with a friction factor m_f=0.5.

The simulation is performed using 200 increments (corresponding to approximately 0.05% reduction in diameter per step) and the convergence criterion is $\Delta u/u < 0.01$, where Δu is the change in the Euclidian norm of the velocities from previous to current iteration and u is the Euclidian norm of the velocities from previous iterations.

2.3. Ingot material

Since the open die forging process is performed with steel ingots preheated to approximately 1200^{o}C, the flow stress of the steel is lowered considerably as compared to room temperature and may be taken to increase not only with increasing strain but also with increasing strain rate. A combination of Hollomon [9] and Norton [10] hardening is used to describe the hardening behaviour:

$$\sigma_o = C\left(\bar{\varepsilon}^{pl}\right)^n \left(\dot{\bar{\varepsilon}}^{pl}\right)^m \qquad (2)$$

where σ_o is the flow stress of the material, C is the strength coefficient, n is the strain-hardening exponent and m is the strain-rate sensitivity exponent. As listed in Table 1 a number of different combinations are investigated to determine how varying hardening may affect the optimum lower die angle.

Table 1. Different combinations of material parameters utilized in the investigation.

C [MPa]	n	m
100	0.0	0.0
100	0.2	0.0
100	0.4	0.0
100	0.0	0.2
100	0.0	0.4
100	0.2	0.2

The exact value of C is not important in the present study because it only affects the flow stress level and not the variation in flow stress within the ingot in contradiction to the values of n and m, which are of interest, since they affect the material flow. An approximate value of C = 100 MPa is taken from Spittel & Spittel [11].

3. Results and discussion

3.1. Plastic flow under different material behaviour

Fig. 3 shows results obtained in simulating forging of an ideal rigid-perfectly plastic material ingot using different lower die angles. The effective plastic strain is used as output to indicate the plastic flow.

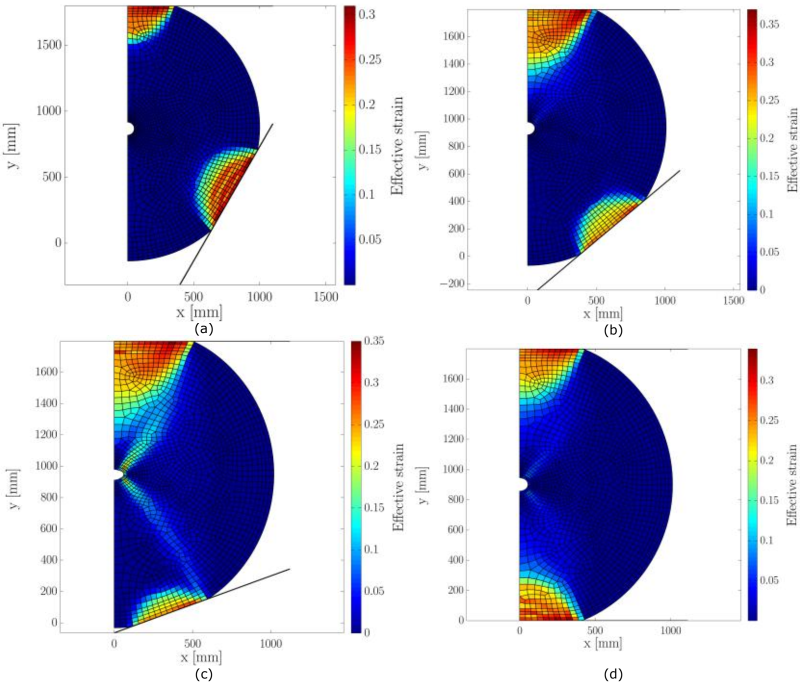


Fig. 3. Effective plastic strain when forging an ingot with constant flow stress, $\sigma_0 = 100MPa$ using lower die angles of 60^o (a), of 100^o (b), of 140^o (c) and 180^o (d).

A clear variation in deformation pattern with varying lower die angle can be seen in Fig. 3, 140^o resulting in the largest plastic straining around the centreline hole.

An example of forging a strain-hardening material can be seen in Fig. 4. Comparing Fig. 3 with Fig. 4 it is noticed that strain hardening influences the flow pattern. Whereas non-hardening material results in deformation confined to small zones of the ingot, the strain hardening distributes the deformation to a larger part. This lowers the maximum strain (compare values corresponding to the same lower die angles).
In case of strain-rate hardening material Fig. 5 similarly shows more widespread deformation than predicted by the ideal-plastic material. The plastic strain is, however, not so evenly distributed as for a strain-hardening material with n = 0.4.

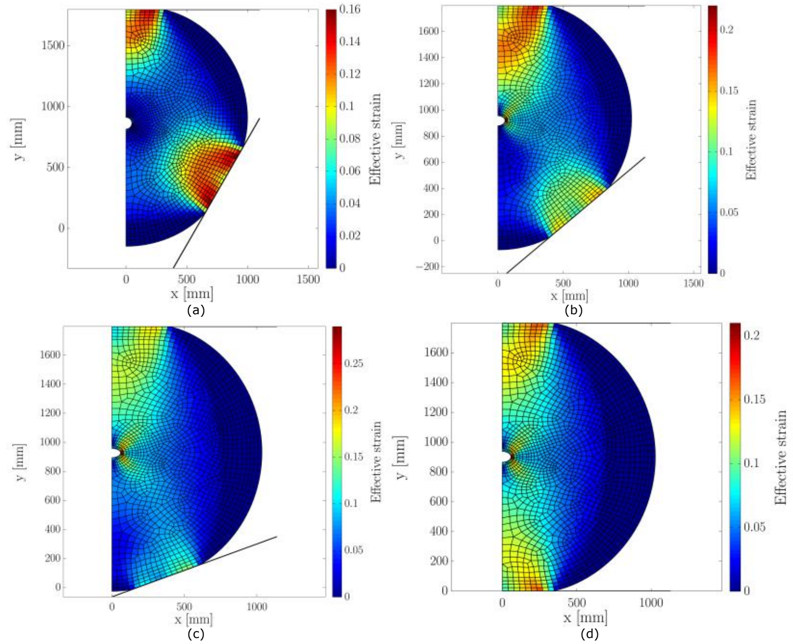


Fig. 4. Effective plastic strain when forging an ingot having a flow stress $\sigma_0 = 100MPa\left(\bar{\varepsilon}^{pl}\right)^{0.4}$ using lower die angles of 60^{o} (a), of 100^{o} (b), of 140^{o} (c) and 180^{o} (d).

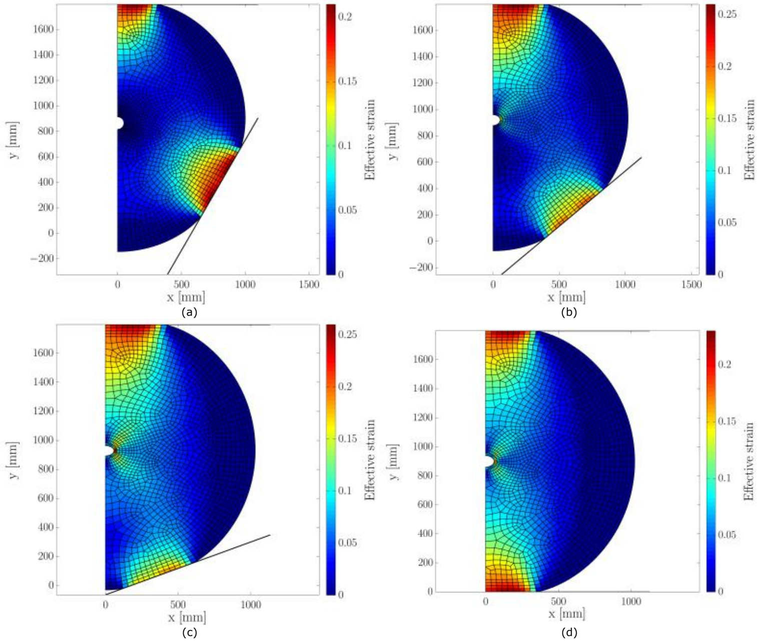


Fig. 5. Effective plastic strain when forging an ingot having a flow stress $\sigma_0 = 100MPa\left(\dot{\bar{\varepsilon}}^{pl}\right)^{0.4}$ using lower die angles of 60° (a), of 100° (b), of 140° (c) and 180° (d).

3.2. *Optimum lower die angles vs. material behaviour and friction*

In order to determine the optimum lower die angle as a function of material hardening behaviour and friction quantitatively, curves displaying the area ratio between initial and final centreline hole cross-section area $A_{ratio} = A_{final} / A_{initial}$ are used to express the amount of centreline porosity closure. The resulting finite element predictions are plotted in Fig. 6 - Fig. 8. It is worth noticing the influence of the inserted friction factor m_f in the overall modelling.

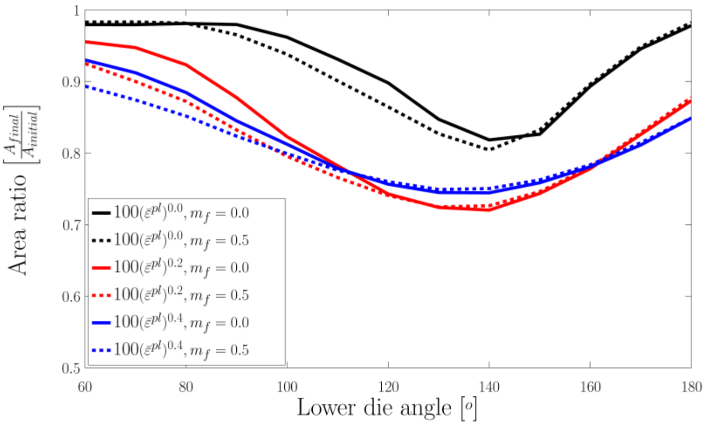


Fig. 6. A_{ratio} as function of strain hardening and friction.

As seen in Fig. 6, the largest degree of closure for the tested strain hardening range is obtained when utilizing a lower die angle of approximately 140^{o}. Friction seems to increase the closure for small lower die angles, whereas the influence is insignificant when applying larger lower die angles.

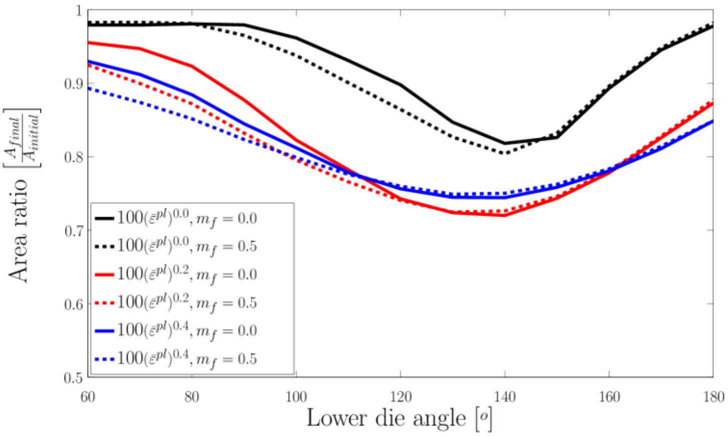


Fig. 7. A_{ratio} as function of strain-rate hardening and friction.

From Fig. 7 it can also be concluded that an optimum lower die angle regarding centreline hole closure is approximately 130^{o}-140^{o} for the entire range of simulated strain-rate hardening. Again friction seems to increase the closure, when applying small lower die angles, whereas it has insignificantly influence in case of larger lower die angles.

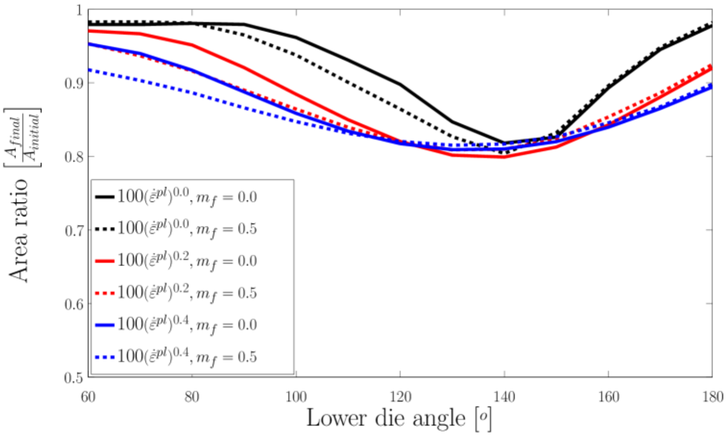


Fig. 8. A_{ratio} as function of combined strain and strain-rate hardening and friction.

In case of material with combined strain and strain-rate hardening as seen in Fig. 8, maximum closure occurs, once again, when applying a lower die angle of approximately 140^{o}. Friction only has a significant influence in case of small lower die angles.

3.3. Forging load

Previous sections lead to the conclusion that material behaviour of the ingot plays a marked influence on the level of centreline hole closure. In general it was found that an increase in either strain or strain-rate hardening gave rise to an increase in centreline hole closure. If material strain hardening is not present due to elevated workpiece temperature a rise in forging speed, which increases the strain-rate, may be feasible to promote closure of the centreline hole. The disadvantage of increasing strain hardening or strain-rate hardening is a larger forging load.

It is also noticed that friction increases the centreline hole closure when applying smaller lower die angle, while it does not significantly influence the closure in case of larger die angles. This is due to increased forging load, which is especially sensitive to friction in case of small die angles. If the lower die is flat (180^o) the load is not increased with increasing friction, see Fig. 9.

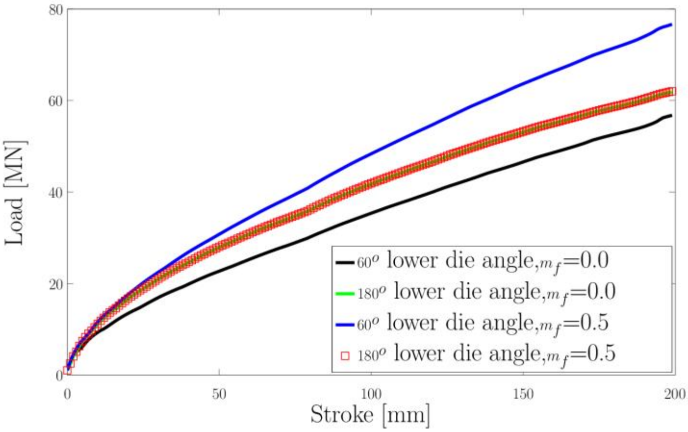


Fig. 9. Comparison of forging loads for different lower die angles and friction factors (m).

4. Conclusion

A numerical investigation of the open die forging process has been conducted with special emphasis on the influence of the mechanical material behaviour on closure of centreline defects e.g. pores. These defects, which originate from the casting process, are modelled by means of a centreline hole. Different strain and strain-rate hardening have been investigated and results indicate that optimum performance regarding centreline hole closure is achieved with a lower die angle of approximately 140^o. Friction is only influencing the amount of centreline hole closure, not the angle at which the optimum performance occurs. Strain or strain-rate hardening gives rise to a larger degree of closure than an ideal-plastic material. Since plane stress deformation has been assumed, the study is in essence limited to open die forging processes of large specimens compared to the width of the dies. This will often be the case forging of large ingots.

ACKNOWLEDGEMENTS

The work is supported by the Strategic Research Center "REWIND - Knowledge based engineering for improved reliability of critical wind turbine components", Danish Research Council for Strategic Research, grant no. 10-093966

Paulo Martins would like to acknowledge the financial support provided by the Velux Foundation during his sabbatical license at the Danish Technical University.

REFERENCES

[1] J. Nasmyth, "Improvements in forging iron," *Journal of The Franklin Institute,* vol. 50, no. 6, pp. 404-408, 1850.

[2] W. Johnson, "Indentation and forging and action of Nasmyth's Anvil," *Engineer,* vol. 205, no. 5328, pp. 348-350, 1958.

[3] H. Keife and U. Ståhlberg, "Influence of pressure on the closure of voids during plastic deformation," *Journal of Mechanical Working Technology,* vol. 4, no. 2, pp. 133-143, 1980.

[4] U. Ståhlberg, H. Keife, M. Lundberg and A. Melander, "A study of void closure during plastic deformation," *Journal of Mechanical Working Technology,* vol. 4, no. 1, pp. 51-63, 1980.

[5] S. P. Dudra and Y. T. Im, "Analysis of void closure in open-die forging," *International journal of machine tools & manufacture,* vol. 30, no. 1, pp. 65-75, 1990.

[6] P. Christiansen, J. H. Hattel, P. Kotas, Lászlo and V. , "Modelling the void deformation and closure by hot forging of ingot castings," *1st International Conference on Ingot Casting, Rolling and Forging,* vol. 1, pp. 1-9, 2012.

[7] P. Christiansen, J. H. Hattel, N. Bay, L. M. Alves and P. A. F. Martins, "Open die forging of large shafts with porosity defects - physical and numerical modelling," 2013.

[8] C. V. Nielsen, W. Zhang, L. M. Alves, N. Bay and P. A. F. Martins, Modeling of Thermo-Electro-Mechanical Manufacturing Processes, 1. ed., Springer, 2013.

[9] J. H. Hollomon, "Tensile Deformation," *Transactions of the American Institute of Mining and Metallurgical Engineers,* vol. 162, pp. 268-290, 1945.

[10] F. H. Norton, The Creep of Steel at High Temperatures, 1. ed., McGraw-Hill, 1929.

[11] M. Spittel and T. Spittel, "Steel symbol/number: 42CrMo4/1.7225," in *Landolt-Börnstein - Group VIII Advanced Materials and Technologies*, vol. 2C1, Springer-Verlag Berlin Heidelberg, 2009.

[12] S. L. Semiatin (editor), Forming and Forging, 9. ed., vol. 14, ASM International, 1998.