Finite element modeling evaluation of a void closure criterion using a multi-scale approach during hot rolling

edited by: C. Pondaven, B. Erzar, A. Spadaccini, M. Grion

The hot rolling of long products is a manufacturing process aiming to refine the microstructure and to guarantee the internal soundness of cast products by contributing to the healing of shrinkage porosity. The understanding of the mechanism involved in the latter phenomenon is necessary to improve the final mechanical properties of rolled products. The pore closure is strongly connected to the thermomechanical loading and to the morphology of the voids respecting to the loading direction. These multiple parameters involved make it thus difficult the application of predictive mean-field model to assess the closure state of voids during complex industrial forming routes.
In this study, a multi-scale full-field approach using Representative Volume Element (RVE) is applied to study the evolution of an explicitly modeled spherical void during the rolling process. This multi-scale approach allows modeling the evolution of voids with dimensions representatives of shrinkage porosity. observed in blooms in an acceptable computation time. A Finite Element model of the studied rolling mill is firstly developed to extract the thermomechanical loadings during the rolling. The loadings of each rolling pass are then applied as boundary conditions of RVE containing a single pore. The evolution of dimensions of the explicitly modeled void is eventually compared with the value of a simple mean-field criterion to evaluate its capacity to predict the void closure capacity of the studied rolling route.

KEYWORDS: PORE CLOSURE, FINITE ELEMENT MODELING, MULTISCALE, HOT ROLLING, REPRESENTATIVE VOLUME ELEMENT, SHRINKAGE POROSITY

INTRODUCTION

The hot rolling of long products is a forming process aiming to reach simultaneously the needed dimensions of rolled products while refining the microstructure and reducing the internal defects generated during the casting. This improvement of internal soundness is interesting to guarantee the fatigue performance and the mechanical properties of the parts manufactured from rolled products.

The current study is focused on the closure of shrinkage porosity generated during the casting of steel. This phenomenon is strongly connected to the thermomechanical loadings applied to the voids during the forming operations. In fact, the impact of high effective strain level was identified by Lee et al. [1] as a factor promoting the void closure. The stress state applied during the forming process also has an impact on void

Corentin Pondaven,
Benjamin Erzar
ABS Centre Métallurgique, France

Andrea Spadaccini,
Matteo Grion
Acciaierie Bertoli Safau (ABS), Italy

closure. The lower the negative triaxiality ratio depicting a compressive state is, the faster is the void closure as identified by Saby et al. [2]. The closure kinetics is also in relation with the initial dimensions and orientations of the cavity regarding the loading orientations as identified by Chen and Lin [4]. The authors therefore defined a void shape factor to describe the void geometry and study its impact on void evolution. This defined shape factor is presented in equation (1), where Si is the shape factor in the i direction of loading (x, y or z), D_x, D_y and D_z are respectively the projected dimensions of the pore in the x, y and z direction.

$$S_x = \frac{2D_x}{D_y + D_z},\ S_y = \frac{2D_y}{D_x + D_z} \text{ and } S_z = \frac{2D_z}{D_x + D_y} \quad (1)$$

To evaluate the capacity of void closure of a forming process, Tanaka et al. [5] proposed the hydrostatic integration defined in equation (2) as an indicator of void closure. In this equation, T_x is the triaxiality defined by the ratio of the mean stress over the equivalent stress and ε_{eq} is the equivalent strain.

$$Q = \int_0^{\varepsilon_{eq}} -T_x \mathrm{d}\varepsilon \quad (2)$$

Using this indicator, Kakimoto et al. [3] defined a threshold value of Q ≥ 0.21 to observe the complete closure of porosity during a single pass process. Concerning multi-pass processes, a threshold of 0.85 is proposed by Kukuryk [6] to observe the closure with an alternation of forming direction. This difference of thresholds highlights the limitations of this kind of criterion that must be linked with the specificity of the studied metal forming route. More advanced criterion integrates void aspect ratio and dimensions to predict the final evolution of the voids as the Cicaporo criterion proposed by Saby et al. [7]. This criterion is, however, not able to model the pore evolution on forming processes including several directions of loading.

To overcome these limitations, simulations with explicitly modeled void can be performed to study their closure during the forming process. The difference of scale between the formed products, with initial cross section about one meter, and the internal pores, with initial dimensions about ten millimeters, imposes to perform this type of simulation using scale transition with Representative Volume Elements (RVE) using the thermomechanical loading of the full-scale process as boundary conditions.

In the present study, the closure behavior of a single spherical void with an initial diameter of 10 mm located in the center of a bloom section is studied using a full-field approach in simulations. The pore evolution of the explicitly modeled pore is studied during a rolling sequence performed on the Rotoforgia mill of ABS in Italy. The sequence is composed of eight rolling pass presenting alternating direction of forming to reduce an initial round bloom with a diameter of 750 mm to a round section of approximately 440 mm. The results of the full-field simulations are then faced with the observed Q value of each pass to evaluate the capacity of this criterion to estimate the pore closure during the selected rolling sequence.

METHODS

All the simulations presented in the current study are done using the Forge NxT 3.2 software developed by Transvalor. The steel studied is a 35CrMo4 steel modeled by a Hensel-Spittel law.

The studied rolling sequence is firstly modeled using a full-scale 3D simulation model. The thermomechanical loadings experienced by the center of the bloom are then extracted from the full-scale model using a sensor. They are then applied as boundary conditions on RVE containing a single pore to model the evolution of the cavity during each rolling pass explicitly. The temperature is imposed overall the RVE to follow the temperature loss observed on the full-scale model. The mechanical loadings are reproduced using the boundary conditions definition described by Li et al. [8]. It means that in the first hand, the displacements are imposed in the transverse direction of rolling, y and z direction, corresponding to the direction of rolling loads. The stress is, on the other hand, imposed on the face perpendicular to the longitudinal rolling direction x, the direction of the bar elongation. The initial RVE containing a single spherical pore is presented in Fig. 1 with a schematic representation of the boundary conditions used in simulations.

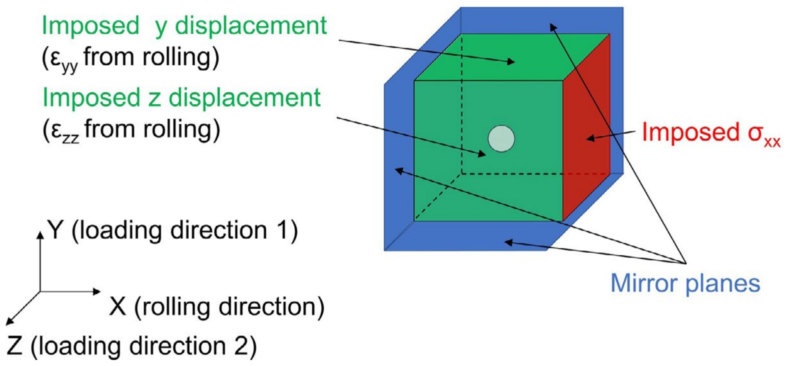

Fig.1 - Schematic representation of the RVE containing a single spherical void.

The RVE dimensions are initially of 40x40x40 mm^3 to obtain RVE dimensions of at least three times larger than the pore dimensions in all directions as defined by Saby et al. [2]. After each pass, the volume and the projected dimensions of the void are extracted. The pore evolution is thus evaluated by the calculation of the ratio of its current volume over its initial volume. The geometry is then integrated into a new RVE with parallelepiped shape suited to the new dimensions of the void to apply the loadings of the following pass.

The full-field model provides thus information on the thermomechanical fields and allows the evaluation of post process criteria such as Q whereas simulations with RVE provide the explicit evolution of the void.

RESULTS AND DISCUSSION

Void evolution results

The evolution of the volume ratio of the single pore during the rolling sequence is presented in Fig. 2. The volume ratio evolution is depicted using disk marks and is showing an advanced closure of the void after the fifth pass of rolling.

Concerning the evolution per pass depicted using the bar diagram, one can notice the effect of the change of the loading direction, materialized by the dashed lines on the Fig. 2, by the observations on void volume ratio per pass higher than one for the third pass which follow a loading direction modification.

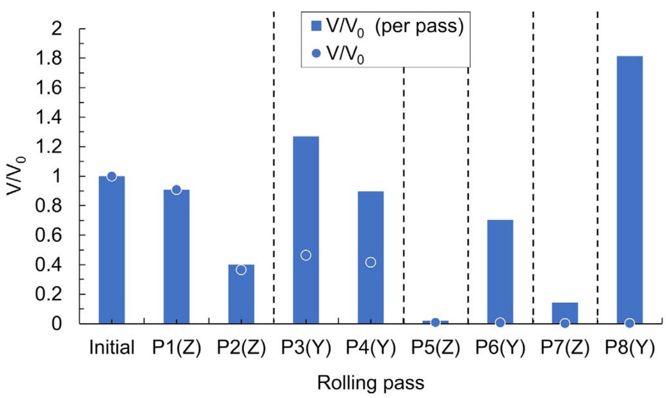

Fig.2 - Void volume ratio evolution during the rolling sequence.

Void evolution associated with the hydrostatic integration

The void volume ratio per pass obtained using the RVE simulation is plotted in Fig. 3 with the corresponding Q amplitude observed per rolling pass on the full-scale model. On the global rolling sequence, one can note that the overall hydrostatic integration value is Q = 0.42 and especially Q = 0.26 after the fifth pass where the initial void is presenting an advanced state of closure.

Concerning the Q amplitude and the void volume ratio per pass, high values of Q amplitude are observed for the pass P2, P4 and P5 which respective value of 0.08, 0.07 and 0.1. The corresponding void volume ratio are 0.4, 0.9 and 0.02. Other high Q values are observed for P6 and P7 with respective value of 0.09 and 0.07.

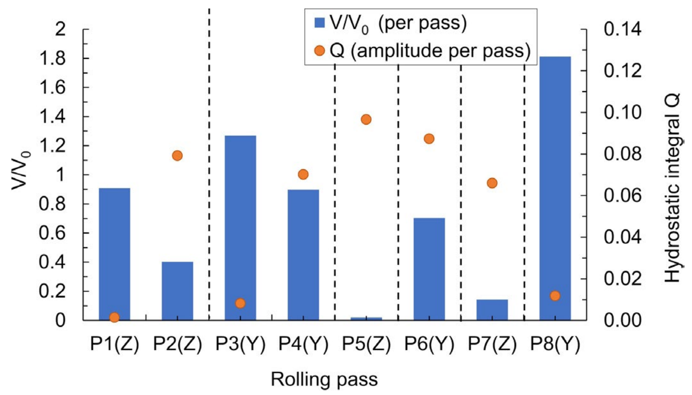

Fig.3 - Hydrostatic integration amplitude per pass during the rolling sequence and void volume evolution per pass

DISCUSSION

The results presented in Fig. 3 highlight the lack of correlation between high Q amplitude observed during a rolling pass and the corresponding void reduction ratio. This observation is especially significant for the second and the fourth pass of rolling which are presenting similar Q amplitudes and are performed after a rolling pass using the same loading direction.

Concerning this aspect, the analysis of the shape factors of the void given by the Fig. 4 a) could provide an explanation for these discrepancies. In fact, the shape factor of the pore in the loading direction is more favorable for the second pass with a value of 0.65 in comparison with the shape factor of 1.24 for the fourth pass which is depicting an elongated void in the forming direction. The stronger impact of the shape of the pore over the applied thermomechanical loading is also confirmed by the correlation diagram presented in Fig. 4 b). On this figure, the eighth pass is omitted given the advanced state of closure of the void after this pass which makes the results non-interpretable given the residual cavity dimensions are approaching the meshing size. Regarding the other passes, a good correlation is observed between the volume reduction ratio per pass and the initial shape factor before each pass. The hydrostatic integration depicted by the areas of the disks is rather unrelated to the observed void volume reduction ratio per pass. This finding confirms the strong impact of the void shape on the closure phenomenon and confirms the interest of integrating these parameters in mean-field models.

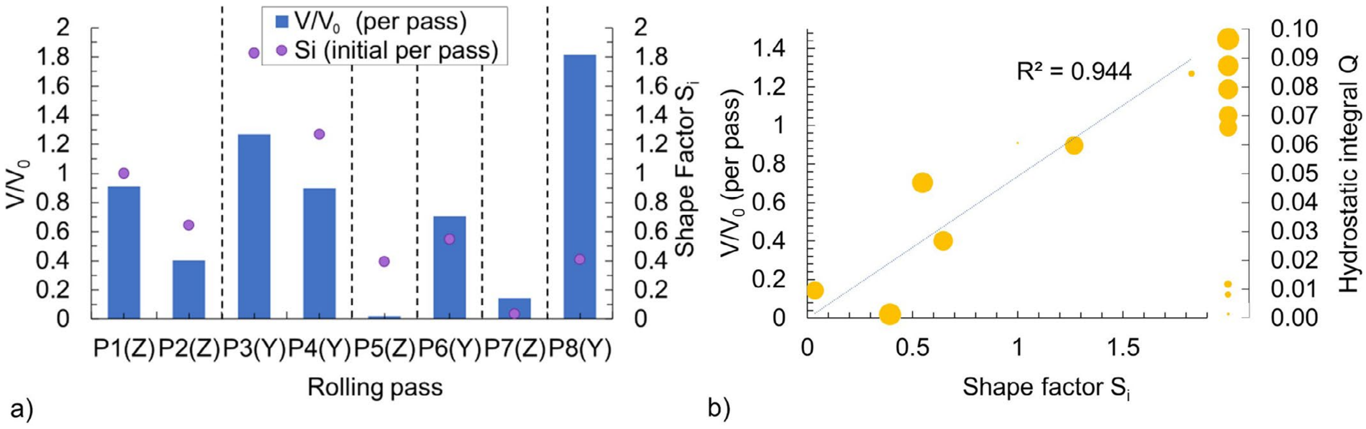

Fig.4 - a) shape factor Si before pass and void volume evolution per pass b) correlation diagram of void volume ratio in respect with the shape factor Si (Q modeled by the area of the marks).

This strong dependence to the shape factor is also highlighting that the analysis of void evolution by only regarding the Q value is insufficient for comparing two similar rolling routes in terms of porosity closure capacity especially for multi-pass processes. In fact, each modification of the loading (roll gaps, initial temperature gradient in blooms ...) will affect the final shape of the void and thus its shape factor which will be modifying its closure behavior on the following passes for the same initial void. Analysis using the Q factor are therefore only appropriate for comparing two single pass processes using identical initial pores.

Eventually, the overall Q needed to obtain an advanced closure of the void during the selected rolling sequence using the VER approach, Q = 0.26 after the fifth pass, this value is way inferior of the threshold of 0.85 observed in the literature for multi-pass forming process. One can nevertheless note that this result is obtained with a simple spherical void and it may not totally represent the complexity of real pores closure with tortuosity. This observation still highlights the too conservative aspect of the threshold value of Q to evaluate the void closure. The application of this method needs in fact to identify a specific threshold for each studied forming routes with multiple initial void geometries. This use of this factor alone is thus not well suited for industrial applications because of its limited possibility of generalization.

SUMMARY

In the present paper, a methodology is described to explicitly model the evolution of shrinkage porosity during an industrial rolling pass using simulation. This methodology is then applied to evaluate the capacity of a simple mean-field indicator to evaluate the closure of a void and emphasize the limited information provided by the hydrostatic integration during multistage forming process even for comparing rolling routes with minor modifications.

This study highlights the interest of the method to validate mean-field criteria in a context of an industrial forming process. As a perspective, this kind of approach could be considered to analyze the evolution of real pore geometries from microtomography to integrate the tortuosity aspects of the defects and improve the understanding of the pore closure phenomenon during the rolling of long products.

REFERENCES

[1] Lee YS, Lee SU, Van Tyne CJ, Joo BD, Moon YH. Internal void closure during the forging of large cast ingots using a simulation approach. J Mater Process Technol 2011;211:1136–45. https://doi.org/10.1016/j.jmatprotec.2011.01.017.

[2] Saby M, Bernacki M, Roux E, Bouchard P-O. Three-dimensional analysis of real void closure at the meso-scale during hot metal forming processes. Comput Mater Sci 2013;77:194–201. https://doi.org/10.1016/j.commatsci.2013.05.002.

[3] Kakimoto H, Arikawa T, Takahashi Y, Tanaka T, Imaida Y. Development of forging process design to close internal voids. J Mater Process Technol 2010;210:415–22. https://doi.org/10.1016/j.jmatprotec.2009.09.022.

[4] Chen M-S, Lin YC. Numerical simulation and experimental verification of void evolution inside large forgings during hot working. Int J Plast 2013;49:53–70. https://doi.org/10.1016/j.ijplas.2013.02.017.

[5] Tanaka M, Ono S, Tsuneno M. Factors contributing to crushing of voids during forging. J Jpn Soc Technol Plast 1986;27:927–34.

[6] Kukuryk M. Experimental and FEM analysis of void closure in the hot cogging process of tool steel. Metals 2019;9. https://doi.org/10.3390/met9050538.

[7] Saby M, Bouchard P-O, Bernacki M. A geometry-dependent model for void closure in hot metal forming. Finite Elem Anal Des 2015;105:63–78. https://doi.org/10.1016/j.finel.2015.07.003.

[8] Li X, Liebsch C, Hirt G, Lohmar J. Modelling of void healing in hot rolling due to recrystallization. Prod Eng 2020;14:43–52. https://doi.org/10.1007/s11740-019-00938-8.

TORNA ALL'INDICE >