Journal of Materials Processing Tech. 259 (2018) 235–242

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

journal homepage: www.elsevier.com/locate/jmatprotec

Experimental and FE analysis of void closure in hot rolling of stainless steel

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ARTICLE INFO

Keywords:
Hot rolling
Finite element method (FEM)
Void closure
Geometrical indexes
AISI 316L

ABSTRACT

Casting metal products are characterized by undesired void defects due to the shrinkage occurring during the solidification of molten material. In order to deliver safe and sound components satisfying the customer requirements, these defects need to be reduced or if possible eliminated. Hot metal forming processes can be used for this purpose therefore, the calibration of their parameters is a fundamental task. In this paper a study of the void closure during hot rolling of 316L stainless steel slabs coming from continuous casting has been conducted. The effects of the hot rolling main parameters (i.e. percentage of reduction, cooling time, and side of reduction) on void closure index have been investigated by means of FE analysis. Data coming from experimental tests performed by Cogne Acciai Speciali S.p.a. were utilised to validate the model and the research results. A correlation between void closure indexes and the residual voids along the hot rolled slabs axis was found for AISI 316L stainless steel. Moreover, new geometric indexes depending on the rolling parameters were defined. Also in this case a correlation between these new indexes and the void closure was found.

1. Introduction

Continuous or ingot casting processes produce parts affected by voids because of the shrinkage occurring during the metal solidification. These defects are irregular in shape and size and their location within the material depends on the casting conditions. Generally, these defects are mainly located along the longitudinal axis of the part as shown in Fig. 1.

Hot metal forming processes (such as rolling, forging, and cogging) are usually utilised to reduce, or when possible to close, these voids. Consequently, the choice of the best process and of its working parameters is an important issue.

In the literature, several studies were developed with the aim of analysing the influence of hot metal forming processes on void closure. Stahlberg et al. (1980) analysed the void closure of artificial voids in plane strain forging with parallel dies and they proposed a theoretical model of the phenomenon relating the void closure with the reduction ratio. Banaszek and Stefanik (2006) studied the void closure in forging by means of experimental and FEM analyses. They identified an objective function based on reduction ratio, die speed and material temperature able to find the best set of process parameters minimising the void dimensions. The review paper of Llanos et al. (2008) summarises the results of some researches focused on studying the effect of rolling process parameters on internal voids. By means of experimental and numerical simulation Hwang and Hwang and Chen, 2003 investigated the effect on void closure of reduction ratio, dimension of the internal void, friction factor, and cross-sectional area of the void. They found a value of critical reduction at which the voids are completely closed. Wallerö, 1985 found that during hot rolling the dimension of central voids decreases when reduction ratio is increased by using larger rolls and larger spread. These results are in agreement with the researches of Stahlberg (1986), who showed that large spread plays a positive role in void closure. Chen, 2006 studied the void closure during rolling of porous metal sheets concluding that the relative density of porous material increases (i.e. the dimension of voids decreases) as the reduction ratio, the friction factor and the roll diameter increase. Other studies were focused on the effect of the temperature gradient in the workpiece. In fact, by means of experimental tests Stahlberg and Keife (1992) found that during hot rolling a high temperature gradient in the part, obtained by water cooling, improves the voids reduction. These results are in agreement with the data reported by Lllanos et al. (2008).

From the literature analysis it is possible to conclude that the best effects on void closure are due to thermal gradient between skin and core of the workpiece, to large single pass reduction, to larger rolls diameters, larger spread and friction between slab and rolls.

Once identified the main process parameters affecting the void closure, the definition of a procedure able to predict the void evolution during metal forming processes is fundamental. As reported in the review paper of Saby et al. (2015a) different approaches can be adopted to develop a void closure model. The choice of the suitable approach is related to the utilized strategy (i.e. analytical, numerical, empirical or their combinations) and to the dimensional scale at which the void

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https://doi.org/10.1016/j.jmatprotec.2018.04.033
Received 29 January 2018; Received in revised form 4 April 2018; Accepted 19 April 2018
Available online 23 April 2018

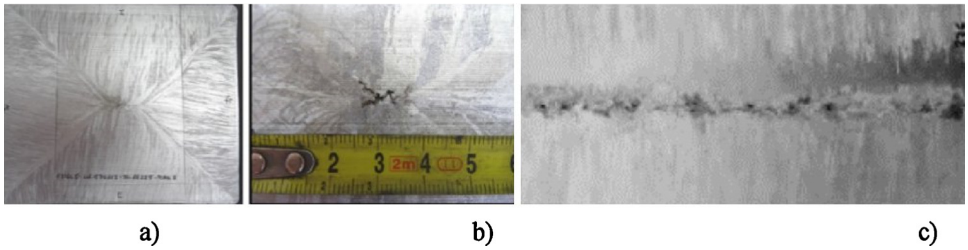

Fig. 1. a) Transversal section of an AISI 316L billet. b) Detail of the central transversal section defect. c) Longitudinal section.

closure is investigated (macroscopic or microscopic scale). The macroscopic or process approaches usually analyse the problem at macro scale with the support of FE software. The FE model can implement internal voids (explicit macroscopic approaches) or not. These approaches are easy to be implemented and allow to identify the influence of the process parameters on void closure at macro scale. On the other hand, it is hard to generalise them since they can represent just a specific forming process. Differently, the approaches performed at micro scale (micro analytical approaches) study the problem from a micromechanical point of view, considering a single void in an infinite matrix. They are difficult to implement and typically they are not able to take into account the change of void shape during deformation. Moreover, the results coming from these approaches are not suitable for industrial applications. Saby et al. (2013) combined these two family of approaches studying the problem at meso scale with the support of FE analysis. In this research a three dimensional Representative Volume Element (RVE) was defined to perform simulations at the micro scale. The mechanical boundary conditions to be applied to the RVE were derived from macroscopic FE simulations of a forming process. The neural networks were used to develop void closure models too. Chen et al., 2011 studied the closure of cylindrical and spheroidal voids in cold flat rolling of Aluminium alloys. Experimental tests and FEM simulations were used to train and validate a void closure neural network model. This model was found accurate and faster than FEA in terms of computational time.

These combined approaches can monitor the void evolution just by means of a closure criterion. Several studies utilised mechanical indexes as closure criterion. Saby et al. (2015a) define one of the most common index to represent void closure: the stress triaxiality ratio (T_X) defined as the ratio between the hydrostatic pressure (σ_h) and the Von Mises equivalent stress (σ_{eq}), as reported in Eq. (1).

$$T_X = \frac{\sigma_h}{\sigma_{eq}} = \frac{\sigma_x + \sigma_y + \sigma_z}{3 \cdot \sigma_{eq}} \tag{1}$$

Tanaka et al. (1986) considered as index to predict void closure the integral (Q) over the cumulated Von Mises equivalent strain ε_{eq} of T_X (Eq. (2)).

$$Q = \int_0^{\varepsilon_{eq}} T_X \, d\varepsilon_{eq} \tag{2}$$

Nakasaki et al. (2006) developed FEM models able to estimate the distribution of Q in forged and hot rolled samples, concluding that a complete void closure can be reached when Q is lower than -0.18. Kakimoto et al. (2010) investigated by means of FE analysis the effect of the shape and position of the void in the billet during hot compression of aluminium samples. In this case the void closure is obtained for values of Q lower than -0.21. Kang et al. (2010) proposed a void closure model based on the evaluation of the Q index over the surface of the void which presents compressive hydrostatic stresses. Chen and Lin, 2013 studied the evolution of the void in the space proposing a three dimensional void closure model based on the estimation of three different values of Q, one for each direction (x, y and z). Other mechanical indexes were proposed in addition to T_X or Q. Saby et al (2015b) developed a void closure model starting from RVE simulations performed by using ellipsoidal voids under different orientation with respect to the loading direction. Recently Chbihi et al. (2017) proposed a new version of the Saby model introducing the influence of the Lode angle θ.

Instead of mechanical indexes Farrugia (2016) suggested geometric process indexes as closure criterion. These indexes, correlated to the mechanical ones, are calculated considering the process parameters such as the reduction ratio, the mean height of the workpiece, the length of contact and so on.

Despite the wide literature concerning void closure in casting products, there is a lack of information on void closure of stainless steel. This research aims to fill this lack studying the effect of hot rolling parameters on the reduction of voids on AISI 316L slabs. A process scale approach was applied for identifying the main mechanical indexes that drive the void closure. In particular, the influence of the integral of T_X (Q) and the equivalent deformation (ε_{eq}) on void closure w investigated. To validate a FE model of hot rolling industrial experimental tests were performed by Cogne Acciai Speciali S.p.a.. Being the dimension of the voids much lower than workpiece dimension as shown by Saby et al. 2013, a void free workpiece assumption was introduced in the developed FE model. In this way the relation between mechanical indexes and void closure was defined for AISI 316L stainless steel. After that, geometric indexes suitable for hot rolling were defined too.

2. Experimental campaign

Experimental tests were conducted by Cogne Acciai S.p.a. on twelve samples of AISI 316L. Each sample had a section of 280 × 340 mm^2 and a length of about 1000 mm and was cut from slabs obtained by continuous casting process. Table 1 provides the chemical composition of AISI 316L stainless steel.

Thin transversal sections of slabs were cut before rolling, in order to evaluate the dimension of the void along the longitudinal axis (Fig. 1). Rolling tests were performed on a Sack Pomini reversible duo mill with flat rolls (Fig. 2). Lower roll diameter was 985 mm while upper roll diameter was 980 mm.

In this study the effects on void closure of thermal gradient, percentage of reduction and side of workpiece on which reduction is performed (shorter or longer side, as shown in Fig. 3) were investigated. In particular, thermal gradient in the workpiece was changed on two levels, obtained by cooling samples after the preheating furnace in air at room temperature (20 °C) respectively for 270 s and 180 s. Furnace permanence was 12 h at 1250 °C, in order to guarantee uniform heating in the samples at the target temperature.

The pass reduction was changed considering a percentage with

Table 1
Chemical composition of AISI 316L stainless steel.

	C% ≤	Mn % ≤	P% ≤	S% ≤	Si% ≤	Cr% ≤	Ni% ≤	Mo % ≤	Others % ≤
AISI 316L	0.03	2	0.045	0.015	1	16.5 – 18.5	10 –13	2 – 2.5	N% ≤0.11