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Study of void closure in hot rolling of stainless steel slabs

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Abstract

Continuous casting products contain void defects due to the shrinkage occurring during solidification. These defects, having different and irregular shapes and sizes, are located and distributed within the material depending on casting conditions. In order to deliver safe and sound products, these voids must be reduced during the subsequent hot forming processes, but it becomes very difficult when slabs are directly hot rolled without any previous forming processes (i.e., cogging), so obtaining a cheaper and more sustainable process chain. Many studies on voids closure present in literature are based on the evaluation of a process parameter called "stress triaxiality ratio". Aim of this research is to optimize the hot rolling process performed to reduce shrinkage voids of the billet due to casting. In particular, the results of a study on voids closure during hot rolling of stainless steel slabs (AISI 316L) coming from continuous casting process are reported. A FE analysis of the effects of the main process parameters of hot rolling on the "voids closure index" were investigated. Afterwards, experimental tests were performed to validate the research from an industrial point of view. A correlation between the void closure index and the final residual void percentage along the rolled slabs was found.

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1. Introduction

Casting products are characterized by the presence of unavoidable void defects due to the shrinkage occurring during solidification of continuous or ingot casting. These defects, having different and irregular shapes and sizes, are located and distributed within the material depending on the casting conditions. Usually the biggest defects are located at the central section of the cast products and are extended along the ingot longitudinal axis.

In order to deliver safe and sound products satisfying the standards, these voids must be reduced or, better, eliminated. Hot metal forming processes (such as rolling, forging, cogging, etc.) are usually used in industry and the calibration of the processes parameters is a main task for this purpose. In literature it is possible to find many studies suggesting the best hot rolling strategies, in terms of process parameters and mill configuration. The effect of the following parameters on void closure was investigated. In particular, in [1-4] the authors studied the influence of pass reduction and of the rotation of the workpiece; the rolls diameter and the width spread were analyzed in [1, 5-8]; the authors focused their attention on workpiece temperature gradient in [1, 4, 9, 10]; while the effect on void closure of friction between workpiece and rolls was investigated by Hwang et al. [3] and Chen et al. [6].

In particular, the most positive effects on voids closure are obtained when a thermal gradient between skin and core of the workpiece exists. Other methods consider the effect of large single pass reduction, or the effect of larger rolls diameters and larger spread. Friction between slab and rolls has also a positive influence. A detailed report on the effects of these parameters can be found in [1].

As far as the void closure criterion is concerned, several studies have been conducted (mainly focused on low carbon steel) suggesting different approaches depending on the applied strategies of analysis (analytical, numerical or empirical) and on the scale at which the void closure is studied. A detailed review of existing models and approaches can be found in Saby et al. [11]. Taking into account the macro and micro scales, two main approaches can be identified investigating the void closure respectively at process-scale and at void-scale.

The present research is aimed to optimize an industrial hot rolling process performed to reduce shrinkage voids due to casting on AISI 316L samples. The void closure is investigated at process scale with the support of FEM modelling. When using this method, a common assumption is that the shape of the defects, usually irregular and variable along the billet in actual parts is assumed to be spheroidal or elliptic. Another limit is related with the computational time. In fact, the implementation of a small void in the workpiece requires a locally high refined mesh so increasing the computational time (some days) and introducing remeshing problems. For these reasons, in the present work the simulations of rolling are performed using a void free workpiece basing on the assumption that, at macroscopic scale, the voids have a negligible influence on the global workpiece deformation. This hypothesis is reasonable when the dimension of the defects is much lower than the dimension of the workpiece, as in our study (Fig. 1), where the ratio between the void area and the billet section is about 0.02%. As a consequence, in a zone far enough from the defect (i.e., 3-5 times greater than the maximum size of voids [12]), the stress-strain state of a billet with voids is the same as of a billet without voids.

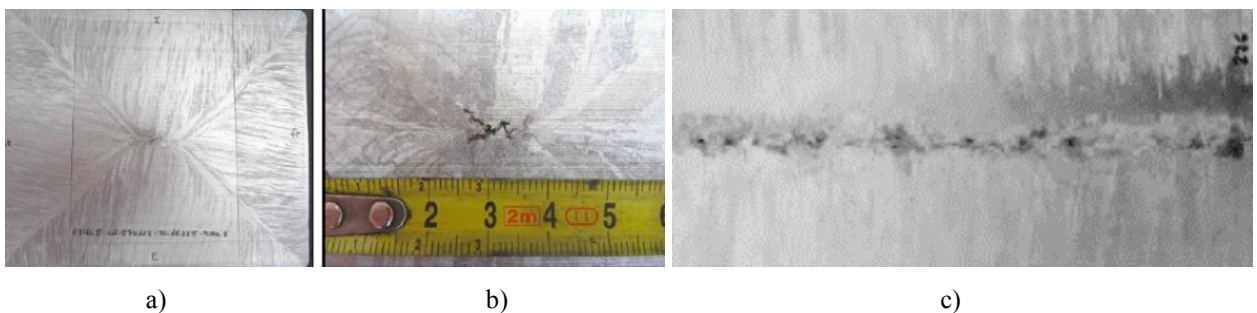


Fig. 1. a) Transversal section of a AISI 316L billet; b) Detail of the central transversal section defect; c) Longitudinal section.

Several studies were published on the identification of void closure criterion, many of them are based on the evaluation of the “stress triaxiality ratio” (T_X) [11]. Equation 1 provides the mathematical expression of T_X defined as the ratio between the hydrostatic pressure (σ_h) and the equivalent stress (σ_{eq}).

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

These studies report that T_X is related with the void closure and can be considered as a void closure index. Tanaka et al. [13] found that the integral (Q) of the stress triaxiality ratio T_X over the cumulated equivalent strain (ε_{eq}), as reported in Equation 2, is a good parameter to predict void closure.

$$Q = \int_0^{\varepsilon_{eq}} T_X d\varepsilon_{eq} \quad (2)$$

Nakasaka et al. [14] observed that when the absolute value of Q is low, the probability of presence of pores in the rolling sample is high. They concluded that for S45C steel a complete void closure can be obtained when Q modulus is higher than 0.18. Kakimoto et al. [15] investigated the effect of shape and position of porosities on void closure during hot compression of pure aluminum 1070 annealed. Experimental tests and FE analysis demonstrated that void closure occurs when Q value is lower than -0.21. Moreover, in [15] it is also shown that shape and position of porosities have an higher influence on void closure with respect to their dimension. The objective of the present paper is first the validation of FE model of void closure for AISI 316L alloy and consequently to identify the influence of the process parameters on void closure in order to optimize the product quality.

2. Experimental tests

Different hot rolling experimental tests were conducted on a Sack Pomini reversible duo mill, using flat rolls. The upper roll diameter was 980 mm while the lower roll diameter was 985 mm. Rolls angular velocity can be set at 40 rpm or 96 rpm. Maximum power of the machinery is 3300 kW. Six samples, made of AISI 316L, were cut from the same billet, having a section of 280x340 mm² and a length of 6500 mm. Each sample had a length of about 1000 mm. To evaluate the initial void defects in the billet, five thin transversal sections were cut along its axis (Fig. 1a). Although, the shape of the porosities changed along the billet axis, the ratio between void area and billet section area was always lower than 0.02 %. In this study, the effect of billet thermal gradient and pass reduction on void closure was analyzed. Billet thermal gradient was varied on two levels. These different thermal gradients were obtained by cooling the workpiece in air at room temperature (20°C) respectively for 270 seconds and 180 seconds. Before cooling, the samples were heated in furnace at 1250°C for 12 hours, in order to guarantee a uniform temperature of the billet from the skin to the core. Three pass reductions were investigated, respectively equal to 40 mm, 60 mm and 80 mm. The billet reduction was realized on the shorter side of the billet. In this manner, the process stability was improved being the longer side of the billet in contact with the rolls.

Table 1 summaries the test parameters and values. The test codification was chosen in order to make the identification of the process conditions easier. The letter refers to the billet thermal gradient (i.e., A: thermal gradient after 270 seconds of cooling; B: thermal gradient after 180 seconds of cooling), while the number refers to the pass reduction (i.e., 40: pass reduction of 40 mm; 60: pass reduction of 60 mm; 80: pass reduction of 80 mm).

All the other process parameters were kept constant. In particular, the angular velocity of the rolls was set equal to 96 rpm and no lubrication was used.

Table 1. Experimental tests setup.

Test code	A40	B40	A60	B60	A80	B80
Pass reduction [mm]	40	40	60	60	80	80
Reduction %	14.3	14.3	21.4	21.4	28.6	28.6
Time out of furnace [s]	270	180	270	180	270	180

3. Finite Element Analysis

Each experimental test condition was simulated with Deform 3D v11 FEM software. The workpiece was modelled as a plastic object and it was meshed with more than 50,000 tetrahedral elements. No void was implemented in the workpiece. The reference system has been set considering the x axis coincident with the longitudinal axis of the billet, the z axis coincident with the direction of reduction and the y axis coincident with the direction of spread.

To describe the thermo-viscoplastic behavior of the AISI 316L alloy, flow stress data were obtained from the empirical model of Hansel-Spittel [16]. In particular, a reduced form of the model was used as shown in Equation 3.

$$\sigma_{eq} = A \cdot \exp(m_1 \cdot T) \cdot \varepsilon_{eq}^{m_2} \cdot \exp\left(\frac{m_4}{\varepsilon_{eq}}\right) \cdot \dot{\varepsilon}_{eq}^{m_3} \quad (3)$$

Where the material coefficients are: $A=2745,39$; $m_1=-0,0026$; $m_2=0,1127$; $m_3=0,1127$; $m_4=-0,02$.

The workpiece temperature was initially set at 1250 °C for all the simulations, while the corresponding cooling time out of the furnace was simulated considering a heat convection coefficient equal to 20 W/(m²K) and an environment temperature equal to 20 °C. A shear stress friction factor between workpiece and rolls equal to 0.7 was used, reproducing the dry experimental conditions.

4. Results discussion

4.1. Experimental results

A preliminary analysis of residual voids after rolling was conducted on the samples using ultrasound (US) non-destructive controls. This technique allows to estimate the void dimension in terms of equivalent flat bottom hole (FBH) and the void position in the billet. Then, FBH can be used as an indicator of the actual defect in billet. The advantage is that it can be easily obtained through fast non-destructive US test. The limitation is that it gives an approximate indication through an equivalent diameter, without information about the shape of the actual defect. Table 2 reports maximum values of equivalent void diameter FBH detected in samples. Since the tests consist in single pass rolling after casting, a coarse grain structure remained in the samples. The US analysis was also used to estimate the percentage of coarse structure. The scattering of FBH measurement was about 1-2 mm while for the percentage of coarse structure was about 5 %.

Table 2. Experimental US results.

Test	A40	B40	A60	B60	A80	B80
Coarse structure %	20-30	50-60	20-30	30-40	20-30	30-40
FBH range [mm]	7-9	8-10	5-6	6-8	5-6	6-7

4.2. FEM results

Thermal gradients after 270 seconds and 180 seconds as predicted by FEM are shown in Fig. 2 where a transversal section of the billet is reported. As expected, the thermal gradient was higher in the case of a cooling time of 270 seconds.

For each simulation, the value of Q parameter in the zone affected by shrinkage porosity was evaluated using the damage output of Deform. The Q value was quite constant along the longitudinal axis, except for entrance and exit zones of the billet. In fact, in rolling process these zones are subjected to different deformations with respect to the central part of the billet. In Fig. 3 the variations of Q as a function of the pass reduction (Fig. 3a and 3b) and of the thermal gradient. (Fig. 3b and 3c) are reported. Table 3 reports the calculation of Q for each test. From Equation 1 a more negative Q parameter refers to heavier compressive stress state.

Table 3. FEM Q results in the zone of the shrinkage porosity.

Simulated test	A40	B40	A60	B60	A80	B80
Q along axis [MPa/MPa]	-0.099	-0.083	-0.189	-0.168	-0.317	-0.267

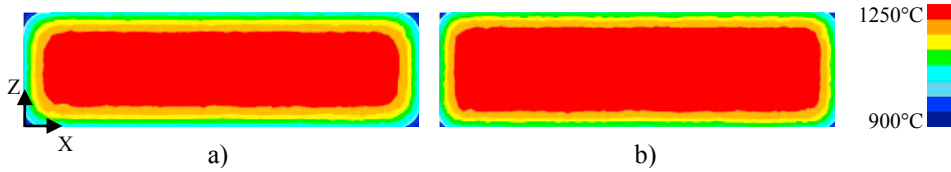


Fig. 2. Thermal gradient after cooling. a) 270 seconds; b) 180 seconds.

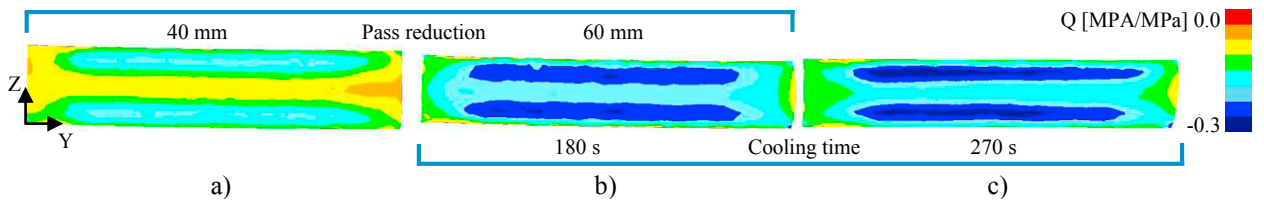


Fig. 3. Q value [MPa/MPa]. a) Sample B1. b) Sample B2. c) Sample A2.

4.3. Results discussion

Despite the uncertainty of the measures, the experimental results reported in Table 2 show that maximum FBH decreases as pass reduction or cooling time increase. In fact, higher pass reduction corresponds to higher compressive state at billet core, and high thermal gradient between core and skin guarantee high deformations at billet core. Similar behavior was reported in literature for AISI 52100 [1].

The FEM results reported in Table 3 show that the Q index becomes more negative as pass reduction or cooling time increase so validating the capability of the Q index in representing the experimental process. The correlation between experimental residual porosity and FEM predicted Q value, is reported in Fig. 4. According to [14], the lowest percentage of residual porosity occurs when the predicted Q value is less than -0.18.

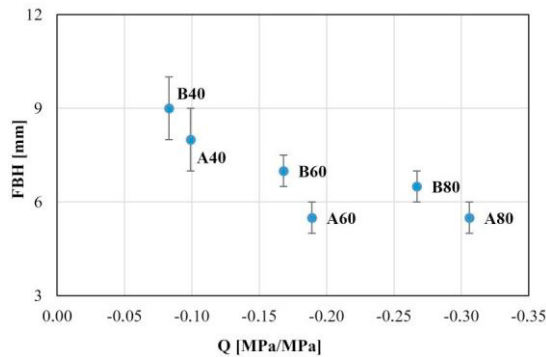


Fig. 4. Correlation between the Q parameter predicted by FEM and the experimental measure of residual porosity.

5. Conclusions

This work describes the results of a study on void closure during hot rolling of AISI 316L steel. The rolling samples provided by continuous casting had a section of 280x340 mm² and a length of about 1000 mm and were preheated in furnace at 1250°C for 12 hours. The effect of thermal gradient and pass reduction on void closure was analysed by FEM simulations and experimental tests. A FE model was designed and validated through experimental tests realised in Cogne Acciai Speciali Spa industries. The so validated model allowed to study how process parameters affect Q index. FE simulations showed that the higher are the pass reduction and the waiting time out of furnace, the lower is the value of Q index. Being low Q values associated to high compressive state in the material, under these process conditions the probability of closing the void increases. Finally, a correlation between Q index and the equivalent void diameter FBH of the residual porosity was found.

The developed FE model allowed to identify some guidelines useful for industrial application: to set high pass reduction, taking into account the mill limits (i.e., torque, power), and to increase the thermal gradient between core and skin.

Future works will study the effect on void closure of the contact side of the billet, in order to evaluate the influence of spread, and of multi passes reduction. In this manner, different set up of hot rolling will be tested in virtual environment in order to optimize the investigated industrial process.

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