High Temp. Mater. Proc., Vol. **30** (2011), pp. 105–111 DOI 10.1515/HTMP.2011.014

The Production of Cracks Evolution in Continuously Cast Steel Slab

Martin Vlado,[1] **Róbert Bidulský,**[2,*] **Lucia Gulová,**[1] **Kristína Machová,**[1] **Jana Bidulská,**[1] **Ján Valíček**[3] **and Ján Sas**[1]

[1] Faculty of Metallurgy, Technical University of Košice, Slovakia

[2] Politecnico di Torino-Alessandria Campus, Alessandria, Italy

[3] Institute of Physics, VSB – Technical University of Ostrava, Czech Republic

Abstract. The prediction of evaluation a U- and V-shaped cracks on the surface and subsurface of a continuously cast steel slab, is investigated during hot rolling. The numerical simulation is carried out by means of FE-code DEFORM 3D. Therefore, an algorithmic decision tree was developed by the C 4.5 program and applied in prediction of surface and subsurface defects behaviour during the numerical simulation of hot rolling. Cracks were selected as a transversal and longitudinal to the rolling direction. In addition to the transversal and vertical U- and V-shaped cracks on the surface; subsurface defect, referred as "circle hole", on the side part of workpiece were evaluated. In terms of surface defects evolution, U-shaped cracks show a deteriorating influence during hot rolling. On the basis of the algorithmic decision tree established, the prediction of cracks evolution (defined before plastic deformation process) during hot rolling is examined.

Keywords. Continuously cast steel slab, hot rolling, defects and simulation.

PACS®(2010). 81.05.Bx, 81.70.-q, 89.20.Ff.

1 Introduction

In the present time, the continuous casting of steel slab undergone significant development and is now widely use. Problems connecting to the formation of surface and subsurface cracks still be largely studied [1–11].

Longitudinal and transversal surface cracks are often found on continuously cast slabs. Often they are located in regions close to the centre line of the slab surface. They are found to be difficult to eliminate during subsequent hot rolling and consequently they will constitute defects on the rolled product [1]. It is clear that in the early detection and elimination of the possible causes of the defect were useful aid for engineers and producers.

Kvačkaj [2–4] classified various types of the surface defects during rolling process transformed from defects in steelmaking process. He categorized defects such as cracks, laps, scratches, surface decarburization, etc. in terms of occurrence, detection, and possibility of confusion with other defects. On the other hand, accurate classification of surface defects on rolled products in terms of their causes and where they were formed in the rolling process was not easy.

Promising technique were numerical and mathematical simulation as well as machine learning methods [12–18], which enables to save time and cost as well as it is promising tool for identifying potential defect roots, both in the slab and in the early stages of hot rolling, and following coils through the production process.

Machine learning methods were applied to hot strip rolling since the more traditional methods have not proved feasible in scale defect modelling or prediction. Scale defects are a common group of surface defects in hot steel rolling, and due to stringent surface quality requirements it is important to recognize the risk factors that cause scale on the surface of steel products. However, no physical model for scale formation has been formulated so far. The problem for modelling is due to high dimensional variable group with their interactions. A combination of statistical pattern analyses, with appropriate heuristic rules is a promising strategy to achieve an improved reliability in defect detection [16–18].

In the present paper, the numerical simulation of hot rolling in relation to the surface and subsurface defects of a continuously cast steel slab is investigated. On the basis of the numerical simulation results, machine learning method [19, 20] is carried out in order to the prediction of cracks evolution during hot rolling.

2 Experimental Materials and Methods

Table 1 shows the chemical composition (wt. %) of the continuously cast steel slab (low carbon steel S690Al).

In order to prevent the nodes of the rolls from penetrating into the work material, penalty functions according to work [1] were used. The reliability of the theoretical

Corresponding author: Róbert Bidulský, Politecnico di Torino-Alessandria Campus, Viale T. Michel 5, 15100 Alessandria, Italy; E-mail: robert.bidulsky@polito.it.

Received: September 17, 2010. Accepted: October 8, 2010.

C	Mn	Si	P	S
0.042	0.225	0.005	0.004	0.010
Al	**Cu**	**Ni**	**Cr**	**Si**
0.052	0.021	0.012	0.007	0.005

Table 1. Chemical composition of investigated steel in mass % ($\leq$0.003: Mo, Ti, V, Nb, Zr, Sn, Sb).

predictions was checked in a pilot-plant mill of roll radius 0.21 m (referred as a physical simulation). The workpiece had a length of 0.135 m. The other initial dimensions were $h_0 = 0.02$ m and $b_0 = 0.06$ m for obtaining similarity with the rolling schedule of the industrial reference mill.

Surface defects of V- and U-shape cracks and subsurface defects, referred to as "circle" hole, were putted into workpiece and specimen. In terms of orientation to the rolling direction, defects were reported as follows:

- transversal V1-shape crack;
- transversal U2-shape crack;
- longitudinal V3-shape crack;
- longitudinal U4-shape crack;
- subsurface KD5-, KD6- and KD7-shaped cracks.

Figure 1 and Figure 2a, b shows the locations of crack in the workpiece and the specimen before the numerical and physical simulation.

Table 2 shows the dimension of defects.

Six cases of state-defect visual appearance were defined after the numerical simulation:

(1) crack elimination,

(2) persistent defect in preserved shape,

(3) persistent defect in unpreserved shape,

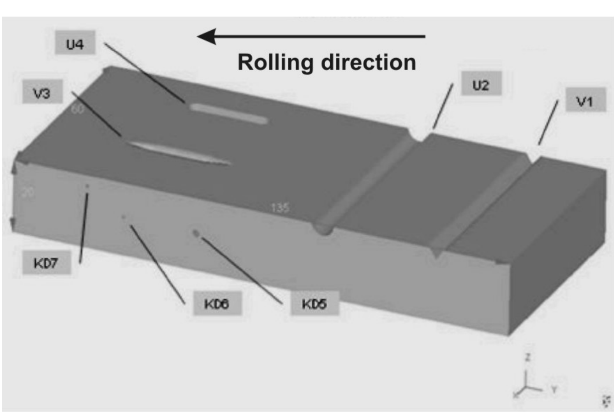

Figure 1. The location of cracks in the workpiece before the numerical simulation.

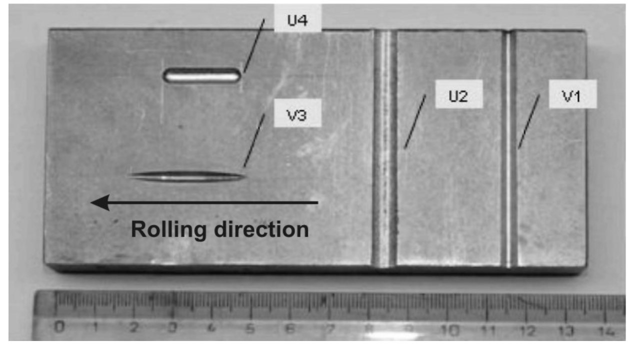

Figure 2a. The location of cracks in the specimen before the physical simulation (top view).

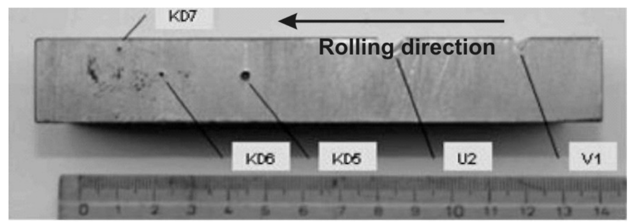

Figure 2b. The location of cracks in the specimen before the physical simulation (sidelight).

transformation of originating defect to secondary defect, which are divided to:

(4) crack development; generation of depressions and holes,

(5) crack development; generation of lap,

(6) crack development; generation of depressions, holes and lap.

An algorithmic decision tree was developed by the C 4.5 program and applied in prediction of defects behaviour during the numerical simulation of hot rolling. Input data of the algorithmic decision tree includes:

- defect dimensions;
- defects orientation to the rolling direction;
- temperature and deformation regime of simulation
- state – defect visual appearance after the numerical simulation.

Five parameters were used in order to describe the crack behaviour (Table 2):

- depth of crack,
- width of crack,
- length of crack,
- radius of crack and
- diameter of crack.

No.	Depth of crack h_0 [m $\cdot 10^{-3}$]	Width of crack b_0 [m $\cdot 10^{-3}$]	Length of crack l_0 [m $\cdot 10^{-3}$]	Radius of crack r_0 [m $\cdot 10^{-3}$]	Diameter of crack d_0 [m $\cdot 10^{-3}$]
V1	3	4	60	–	–
U2	–	6	60	3	–
V3	1.9	3	29.9	–	–
U4	–	4	20	2	–
KD5	7.5	–	–	–	2
KD6	5	–	–	–	1
KD7	2.5	–	–	–	1

Table 2. Dimensions of crack before simulation.

No.	T_0 [K]	T_ε [K]	ε [%]
1	1523	1453	30
2	1523	1453	40
3	1523	1453	60
4	1473	1373	30
5	1473	1373	40
6	1423	1023	20
7	1423	1323	30
8	1423	1323	40
9	1423	1373	50
10	1423	1373	60
11	1423	1373	80

Table 3. Temperature-deformation regime.

Temperature-deformation regime used in both experiments was listed in Table 3, where: T_{H} – heating temperature [K], T_ε – deformation temperature [K], ε – the amount of deformation [%].

The processing conditions are listed in Figure 3.

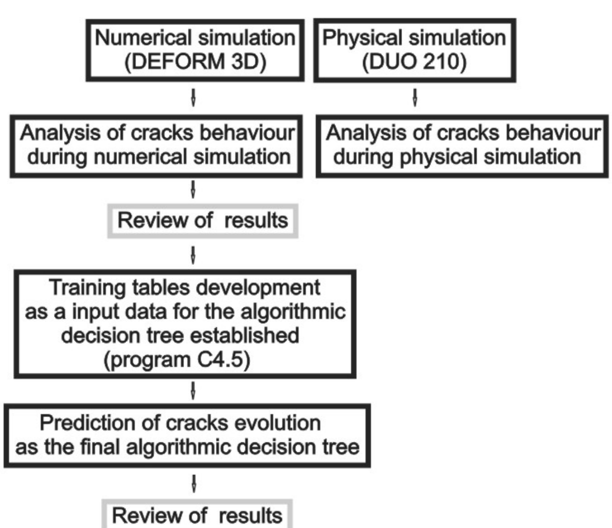

Figure 3. Processing conditions.

3 Results and Discussion

Table 3 presents state-defect visual appearance after the numerical simulation for given temperature-deformation regime. Table 4 present example only the worste results of simulation, surface U-shape cracks, that all these cracks transformated to secondary defects. The results show that primary defects are presented, mainly in U-shapes cracks.

It appears from these Table 4 and Table 5 that the amount of deformation is preferred effect on the crack elimination than other factors. Thermal factor should be important in industry conditions in terms of physic-chemical processes during the heating as a result of oxide influences on the defects. There are many possible sources of oxidation throughout the whole continuously cast steel slab process, including slab cracks, pinholes and other [12–21]. In respect to this, is necessary realised the heating either in protective or artificially defects to furnish by plug in order to prevent from further oxidisation. Therefore, our simulation processes was selected without oxide influence on the crack developments.

In terms of temperature-deformation parameters is important amount of deformation. For the U2- and U4-shaped, the numerical simulation show that development of primary defects are presented until the strain exceed 80 %. The V-shaped crack reliably eliminated primary defects, independent on the defect dimensions and temperature until the application of strain 60 %. Crack elimination was obtained also in two another conditions ($T_0 = 1473$ K, $\varepsilon = 30\,\%$, $h_o = 0.03$ m and $T_0 = 1573$ K, $\varepsilon = 60\,\%$, $h_o = 0.03$ m).

Heating temperature (1150–1250 °C) plays only marginal role that the amount of deformation occur in the range of 30–60 %. Zhang et al. [22] revealed that the temperature field in the shell of slab is not uniform, so the thermal stress will occur in the shell. If the thermal stress and mechanical stress caused by pulling slab are big enough, the cracks would appear, especially on the surface of slab, as the thermal stress reaches the maximum value on

No.	Dimensions of crack before simulation		Dimensions of crack after simulation		State-defect visual appearance	
	v [m·10^{-3}]		NS	PS	NS	PS
V1	$h_{0,1}$	3	0	0.96	(1) crack elimination during hot rolling	(3) persistent defect in unpreserved shape
	$b_{0,1}$	4	0	7.04		
	$l_{0,1}$	60	0	64.41		
U2	$h_{0,2}$	3	h = 0	h = 0.43	(5) crack development; generation of lap	(3) persistent defect in unpreserved shape
	$b_{0,2}$	6	0	9.27		
	$l_{0,2}$	60	0	63.47		
V3	$h_{0,3}$	1.9	0.4	0.54	(4) crack development; generation of depressions and holes	(2) persistent defect in preserved shape
	$b_{0,3}$	3	3.39	2.24		
	$l_{0,3}$	29.9	0	55.65		
U4	$h_{0,4}$	2	h = 0.25	h = 0.56	(6) crack development; generation of depressions, holes and lap	(6) crack development; generation of depressions, holes and lap
	$b_{0,4}$	4	3.23	3.94		
	$l_{0,4}$	20	0	35.85		
KD5	$d_{0,5}$	2	b = 4.5	b = 4.75	(3) persistent defect in unpreserved shape	(3) persistent defect in unpreserved shape
	$h_{0,5}$	7.5	1.6	6.38		
KD6	$d_{0,6}$	1	b = 1.68	b = 2.8	(3) persistent defect in unpreserved shape	(3) persistent defect in unpreserved shape
	$h_{0,6}$	5	0.8	4.65		
KD7	$d_{0,7}$	1	b = 0	b = 2.51	(1) crack elimination during hot rolling	(3) persistent defect in unpreserved shape
	$h_{0,7}$	2.5	0	2.23		

Table 4. State-defect visual appearance after the numerical simulation for regime: $T_o = 1423$ K (1150 °C), $T_\varepsilon = 1373$ K (1100 °C) and $\varepsilon = 50\,\%$, NS-numerical simulation, PS-physical simulation.

the slab surface. Due to these facts, heat transfer and heat generation due to plastic deformation have not been taken into account. The contact times are, however, short and the volume of material are large so that the reliability of the present results should not be strongly violated because of this assumption [1].

On the basis of the numerical simulation, the algorithmic decision tree was established. The results are plotted in algorithms for prediction of crack evolution of U-shaped and V-shaped cracks (Figure 4 and Figure 5).

Model predictions are found to be in good agreement with measurements obtained from artificial defect carried out on the mill, mainly in comparison the behaviour of U4-shaped crack during both simulation of hot rolling as well as subsurface circle hole defects. In Figure 6 it is clear visible the crack development and the generation of lap (narrow in the Figure 6).

The similar results obtained by Son et al. [5]; they studied deformation behavior of the surface defects of low carbon steel, and found that the oval-round rolling sequence was effective to make the notches decrease in depth although this rolling sequence could not eliminate the evolved notches. As well Ervasti and Stahlberg [1] and Eriksson [7] carried out the numerical simulations of the V-shaped cracks.

4 Conclusions

The obtained results can be summarized as follows:

1. On the basis of the algorithmic decision tree established, the prediction of cracks evolution during hot rolling is examined.

2. In terms of surface defects evolution, U-shaped cracks show a deteriorating influence during hot rolling.

3. In terms of temperature-deformation parameters is important the amount of deformation. For the crack elimination is necessary to achieve the amount of deformation of 50 % and 80 % in case of V-shaped and U-shaped cracks, respectively.

Acknowledgments

Authors are grateful for supported of experimental works by national project VEGA 1/0035/10 and IGS-HGF VSB TUO-2005-516/6.

l_o [m·10^{-3}]	**b_o [m·10^{-3}]**	**h_o [m·10^{-3}]**	**T_0 [K]**	**T_ε [K]**	**ε [%]**	**Type of crack**	**State-defect visual appearance**
60	6	3	1523	1453	30	transversal (U2)	crack development; generation of lap
20	4	2	1523	1453	30	longitudinal (U4)	(3) persistent defect in unpreserved shape
60	6	3	1523	1453	40	transversal (U2)	(4) crack development; generation of depressions and holes
20	4	2	1523	1453	40	longitudinal (U4)	(3) persistent defect in unpreserved shape
60	6	3	1523	1453	60	transversal (U2)	(1) crack elimination during hot rolling
20	4	2	1523	1453	60	longitudinal (U4)	(4) crack development; generation of depressions and holes
60	6	3	1473	1373	30	transversal (U2)	(1) crack elimination during hot rolling
20	4	2	1473	1373	30	longitudinal (U4)	(4) crack development; generation of depressions and holes
60	6	3	1473	1373	40	transversal (U2)	(5) crack development; generation of lap
20	4	2	1473	1373	40	longitudinal (U4)	(5) crack development; generation of lap
60	6	3	1423	1023	20	transversal (U2)	(2) persistent defect in preserved shape
20	4	2	1423	1023	20	longitudinal (U4)	(2) persistent defect in preserved shape
60	6	3	1423	1323	30	transversal (U2)	(6) crack development; generation of depressions, holes and lap
20	4	2	1423	1323	30	longitudinal (U4)	(4) crack development; generation of depressions and holes
60	6	3	1423	1323	40	transversal (U2)	(4) crack development; generation of depressions and holes
20	4	2	1423	1323	40	longitudinal (U4)	(6) crack development; generation of depressions, holes and lap
60	6	3	1423	1373	50	transversal (U2)	(5) crack development; generation of lap
20	4	2	1423	1373	50	longitudinal (U4)	(6) crack development; generation of depressions, holes and lap
60	6	3	1423	1373	60	transversal (U2)	(5) crack development; generation of lap
20	4	2	1423	1373	60	longitudinal (U4)	(5) crack development; generation of lap
60	6	3	1423	1373	80	transversal (U2)	(1) crack elimination during hot rolling
20	4	2	1423	1373	80	longitudinal (U4)	(1) crack elimination during hot rolling

Table 5. State-defect visual appearance after the numerical simulation for given temperature-deformation regime.

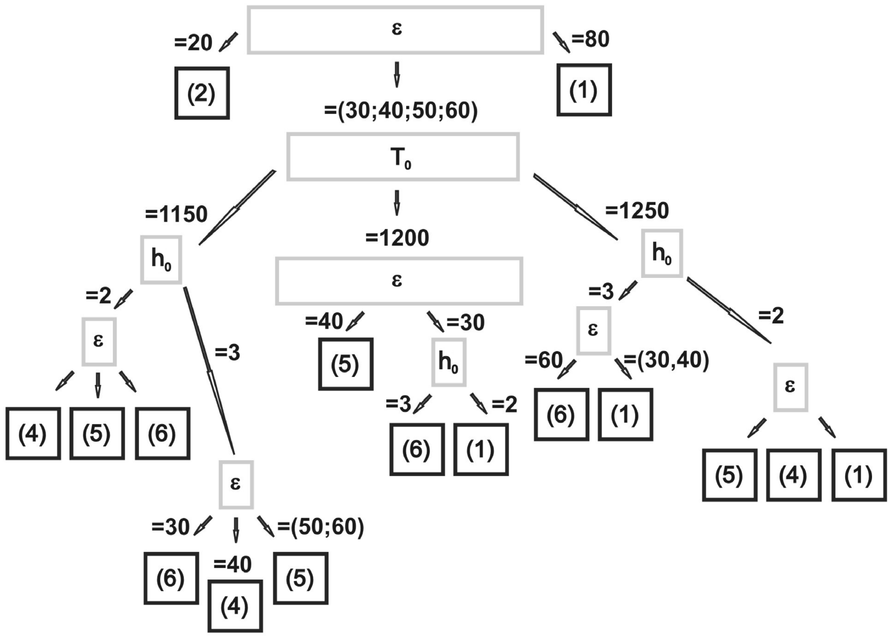

Figure 4. The prediction of U-shaped cracks evolution in continuously cast steel slab.

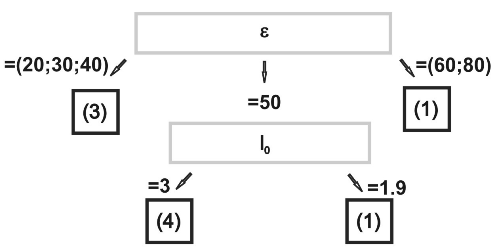

Figure 5. The prediction of V-shaped cracks evolution in continuously cast steel slab.

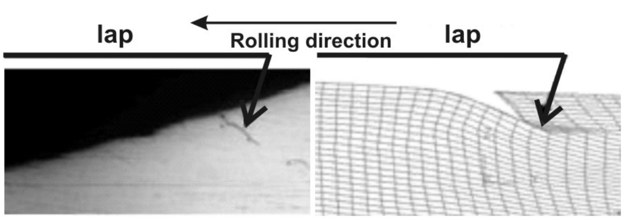

Figure 6. The generation of lap during both simulation ($T_0 = 1423$ K, $T_\varepsilon = 1373$ K, $\varepsilon = 30\,\%$).

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