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pt.

„Application of deep learning approach for identification and classification of scale defects during hot forming process”

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# Introduction

## Motivation

The main requirements of Modern Industry is to create high quality materials, with minimization of costs. Unfortunately, this is very difficult or even impossible to obtain that, using classic methods of production.

Steel industry and hot forming process have same requirements. Direct customers, and next steps of production expect to get high quality products. It causes, that process require constant control quality of product. One of the factors is rating of surface quality. This is a difficult process, because of velocity of hot forming process, multiple different defects and large surface, where we can find defects. One of the known inspections is a visual inspection made by inspector, which observe samples of produced plate. However, technological process provide new, automated solutions. One of the solution is a ASIS (Automatic Surface Inspection System). Main tasks of ASIS is take photos during the process, detection local difference of contrast, which can be a defect, and recognize proper class. The output of ASIS is classified defects map of produced material. This kind of solution allows to limit time for inspections and control of surface. Additional advantage is possibility getting information about state of production.

## Aim of Thesis

Aim of the thesis is to create a classifier of defects which can detect, and classify defect, founded on picture taken during hot production process. Based on local differences of contrast, classifier can detect, and in next step classify the defect. There are multiple different of class. To obtain desirable class, there must be prepared set of classified defects. Based on this set, classifier studies the vision features of pictures, and create a model. This is a typical *blackbox* approach for end user, because it allows to detect defects without specialized knowledge.

As for now, there is many approaches to solve this problem. Many of them is related on artificial intelligence e.g. *decision trees, neural networks etc*. This thesis is focusing on using Neural Networks using Convolutional neural networks (CNN). Convolutional neural networks is a class of deep, feed-forward Artificial neural network that has successfully been applied to analysing visual imagery and classify it. Based on classified set of pictures, solution will try to learn network model. Proper learned model will detect and classify defect. Eventually this solution can be used during hot forming process. Properly trained network provide fast and exact method to detect and classify defects, which can help inspector.

## Content of Thesis

In second chapter, thesis describe hot forming process, current state of sheet metal defect inspection and approximate the theoretical basis phenomenon of scale formation in the hot-forming process. In the next chapter, are presented Classification of defects, and their division. Fourth chapter describe application of deep learning to analysing and classification of pictures. It is focused on *deep learning* and Convolutional neural networks.

# The problem of defects in hot-forming sheets

## Hot forming process

Subject of this thesis is about apply methods of neural networks to classification surface defects of flat sheets. Produced sheets and strips in their section are rectangle, and there have much more width than height. In view of temperature of forming, we can distinguish hot and cold forming process. Thesis is focusing on hot forming process.

Depending on the form, flat steel are divided into: sheets and strips. The sheet is called product which is hot or cold forming, flat with freely formed edges, supplied in form of rectangle sheets with 600 mm width and higher. The strip is called flat product formed on hot or cold, which is rolled into a circle directly after the final operation of forming, etching or continues annealing. Flat steels are used to production of cars, household goods, packing, etc.

Plastic deformation of flat steel at ambient temperature makes their harder, stronger and their changes electrical properties. At the same time, when deformation value increase. In order for the steel to be deformed, without any breaks, they should be restored earlier plastic properties. The phenomenon of reconstruction of the cellular structure, which is leading to recovery of the plastic properties is called recrystallization. Temperature of recrystallization in the absolute scale is described by the following empirical formula:

where Tr is a temperature of recrystallization, and a Ttop is a temperature of melting. For a pure metals the value is equal to 0.4, and for the alloys with the solid structure the value is equals to 0.6.

Hot plastic processing is made above the temperature of recrystallization. Desired shape of sheet or strip is obtained by plastic deformation of the material, between rotating and cooperating rolls. Thesis deals with longitudinal rolling (*Image 1a*), where material performs a translational movement, and rolls with the parallel axes rotate in opposite direction.

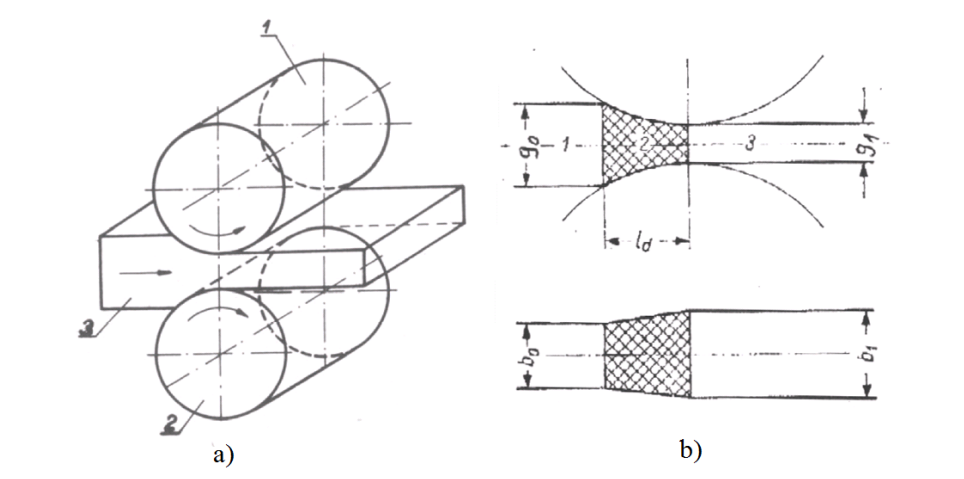


Image 1: a) Longitudinal Rolling, b) Rolling mill

During of the rolling the cross-section is decreased, while the length is growing. Area, where the part of material is deformed is called rolling mill (*Image 1b*). In the rolling mill occurs the reduction of thickness (from g0 to g1), and in the effect are changing: width, cross-section and length of sheet or strip.

Image 2 shows the general concept of the layout of a typical hot rolling mill. The process starts from the loading of the ingot(1) into the furnace(2), which heats it to temperature around 1250 C. Ingots from the furnace will go to the milling line, which leads through the next technological steps. Initial mill(3), which job is initial reduction of a strip, can consists of a single reversing mill or several rolling mills in a similar arrangement. Some rolling mills use an intermediate band winding box (4) to reduce the length of the rolling line and equalization of temperature along the rolled strand. Installation of descaling (5) is responsible for removing scale from the surface of the strip. Group of finishing mills (6) gives the final thickness for the strip. Cooling section (7) sets the winding temperature. One coiler or group of coilers (8) forms the final product – circle of the tape.

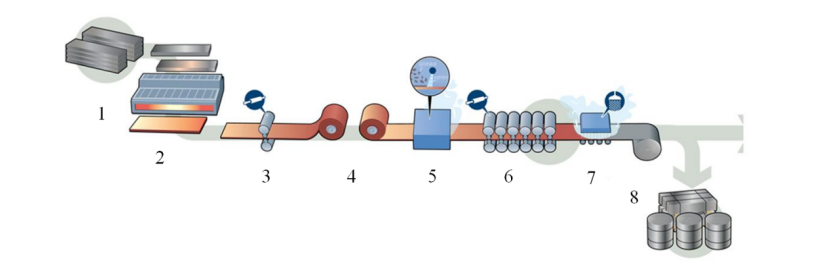


Image 2: Diagram of the hot rolling mill

## The phenomenon of scale formation in the hot forming process

Scale defects are an effect of gas corrosion, when metallic material will be exposed to the environment with oxidizing properties in raised temperature. Reaction products are created, which can be volatile, liquid or solid in case of conditions and plastic composition. Solid parts of material are named scale defects.

The basic type of reaction which causes gas corrosion and forming of scale defects is chemical reaction of oxidation. In case of oxidation of pure divalent metal, it can be change as:  
where M is a metal, and X2 is a oxidation, for example: O2, S2, N2.

After a few seconds of reaction, the scale layer is higher than 10 µm. Their composition and construction differ depending on reaction conditions, reaction environments and time of oxidation. The chemical composition of the metal or alloy, where scale defect is precipitated has a significant influence. Commonly occurring scale defects are two-phase or multi-phase scale defects.

Beginning of reaction, causing formation of scale defect is characterized by the formation of thin scale. That scale is compact and adjacent to the ground (*Image 3*a). If metal can create several persistent compounds with the oxidant, then scale defect will be multi-phase (*Image 3*b). The thickness ratio of scale defect layers depends of temperature of the gas corrosion process. When the temperature growing, the thickness of direct layer adhering to material are growing to. Long oxidant process between metallic core and primary, compact scale defect layer causes creating porous inner layer. *Images 3c and 3d* are showing one-phase and two-phase construction of scale defect at a later stage of its formation.

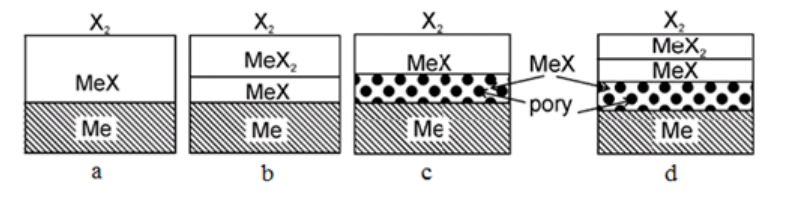
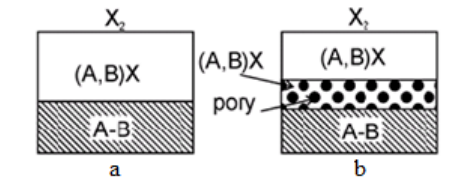


Image 3: Formation of scale defect. a) one-phase in the initial stage of formation; b) two-phase in the initial phase of formation; c) one-phase at a later stage of formation; d) two-phase at a later stage of formation

In case of two-components alloys, where both alloys constituents (A and B) can create chemical compounds with oxidant X in reaction conditions, and assuming that the mutual solubility of the components AX and BX is unlimited, the one-phase scale defect will be created (*Image 4*).

Image 4: Scale formation for compounds AX and BX, which exhibit unrestricted mutual solubility



The other case of mentioned example is situation, when the compounds of two metals and oxidant do not exhibit mutual solubility and metals differ in their chemical affinity to the oxidant. In that case, homogeneous or heterophasic scale could be created. First scale in outside layer contains the only one compound (*Image 5a*). It is an example of selective oxidation(Mrowec and Werber, 1982). Heterophasic scale(*Image 5b*), in outside layer contains a mixture of compounds of both alloy components with an oxidant. This type of scale is formed, for example, on the alloys Fe – Cr in an environment containing oxygen or sulphur as the oxidant. In the case, where the AX and BX compounds have limited mutual solubility under the reaction conditions, it is possible to create two-layer scale with a continuous outside layer.

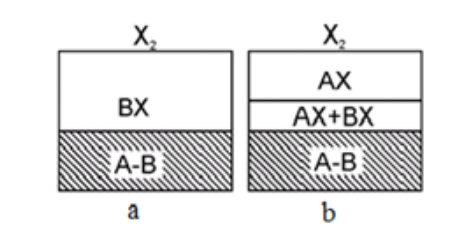


Image 5: Scale: a) two-component in case of selective oxidation; b) heterophasic

In the last example, when the oxidizing component of the atmosphere can diffuse into the alloy and form a compound with a metal with higher chemical affinity (e.g. B), before the alloy constituents manage to diffuse into the surface, on metal A rich alloys, BX compounds will form underneath the layer of BX scale. The area of occurrence distributed BX phase in the surface layer of the alloy is called the internal oxidation zone. On metal-rich B alloys, the scale is formed, builded only from the BX phase, under which an internal oxidation zone may be formed(*Image 6*)



Image 6: Scheme of the structure of the scale and the internal oxidation zone in the case of the formation of a single-phase reaction product, when the chemical affinity of component B is higher than that of component A: a) rich in metal A; b) alloy rich in metal B

## Factors affecting the formation of scale

Formation of scale is depends mainly on the heating temperature, heating time, condition of metal surface, on which metal is formed, the chemical composition of gas, in the working space and the chemical composition of the steel. Scale may be compact and tight, then it is a protective layer, obstructing access of external gas to the metal surface, and thus will stop the oxidation process. The examples of metals, which can create compact scale in higher temperature are e.g. copper, chrome, zinc(Czermiński, 1978)

In the process of scale formation an important elements is the condition of metal surface, which has the effect of gas corrosion, and then the scale is formed. Acceleration of this process may be due to the privileged crystallographic orientation of the metal surface exposed to oxidizing atmospheres(Dobrzański, 2002).

The factor, which facilitates the process of gas corrosion is the mechanical machining of metal. When the internal stresses increase, there is an increase in network defects in the outer metal or alloy layer. As a result of local heating of metal, layers or oxides or hydroxides are formed.

The profile of the metal surface also has an effect on the speed of the descaling effect. If the surface are exposed to the effect of gas corrosion is high and has irregular shapes, then it favours the uneven formation of scale and the occurrence of cracks and micro-voids.

Character of the chemical reactions and the magnitude of corrosion damage is determined mainly by the chemical composition. To gases, which can cause an intense course of gas corrosion include: air, water vapour, carbon compounds e.g. mixtures of CO-CO2 and hydrocarbons, sulfur compounds, e.g. H2S, SO2 and SO3, as well as nitrogen and ammonia. In an industrial atmosphere, a multi-component gas mixture is often found. In such cases, the formation complex, usually multilayer scale is observed. Chemical reactions that decide to the scale formation in these conditions are depending on many factor, which include:

* chemical affinity between the metal and the components of the corrosive atmosphere,
* the rate of formation of individual scale-forming compounds,
* properties of the compounds forming part of scale, above all their state of aggregation and solid solubility in solid state, and susceptibility to formation of multicomponent compounds,
* compactness or porosity of the formed scale and its permeability to the atmosphere and its components.

## Scale defect in the hot forming process

During the hot forming process, where the processed metal resides in the air, there is going to gas corrosion. The result of that process is the formation of a layer of scale on the metal surface. Because the scale layer separates the working rolls from the metal, its properties have a significant impact on the friction and heat exchange between the band and the work roll (Li and Sellars, 1996). Direct result of this interaction is impact on the condition of air and lifecycle of work rolls (Vergne and in., 2001). The parameters, which has impact on the formation of scales, that have been described in the literature are:

* temperature and time of rolling (Andorfer and in., 2003; Bolt and in., 2002; Chen and Yuen, 2000; Ginzburg, 1989; Sun, 2005; Sun and in., 2004),
* thickness of the rolled stand (Blazevic, 1996; Sun, 2005),
* rolling force (Andorfer and in., 2003; Bolt and in., 2002),
* chemical composition of steel (Tan and in., 2001)
* the silicon content in the steel alloy and the heating temperature in the furnace (Ginzburg, 1989)
* unequal cooling of the rolled strand (Chen and Yuen, 2000).

There are many types of defects related to the nature of the scale deposited on the surface of the rolled metal, such as: primary scale, secondary scale, rolled strip, red scale, etc.

There are several to remove scales in the hot forming process, including: mechanical cleaning, high pressure water jet cleaning, etching before cold rolling, flush annealing. In modern rolling mills often used method of removing (sapping) scales is high pressure water jet cleaning (Tiley and Munther, 2009). Pre-scaling is located behind the unloading zone of the rolling mill. After the ingot is released from the furnace, it is fed with a roller conveyor to the pelletizer to remove the primary scale formed during the heating in the furnace. The water pressure in the collector manifold depends on the type of installation and reaches 20 bar. Image 7 is a pictorial drawing of two collectors of a scale ebullator. In the next steps of production, the tape is fed to the initial cage and the scale squeezer located in front of the group of finishing mills.

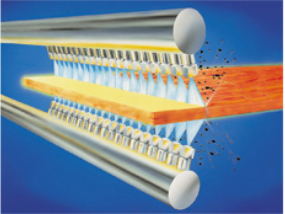


Image 7: Collectors with nozzles to remove rolling scale

# Classification of defects and division of the scale

The goal of this chapter is to show division of scale defects based on vision character and reasons of occurrence. Divided scales was an input to classification system. To learn deep network, there was required to has large dataset with classified scale defects.

## Rolled-in primary scale

Rolled off scale *(Image 8)*, also called sagger (Parsytec-AG, 2005) is a defect classified as surface defect, which surface is characterized by transverse, in relation to the direction of rolling and scale breaks. The size of defect varies from a few millimetres of wide to several centimetres of length. This class can be found locally, mainly at the beginning of strand, with different density of both on its surface. It often occurs with other type of scales, which has not been correctly removed. After the digestion process, the defect can occurs in the form of depression of surface.

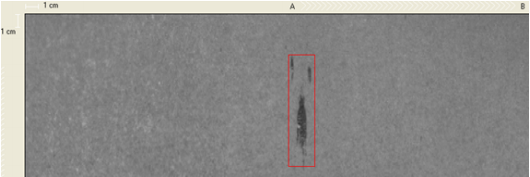


Image 8: Rolled-in primary scale

This is a typical defect among the cases of rolled scale, which is created before the group of finishing frames. It is taken from insufficient removal of the original weight lying on the ingots after leaving the furnace. The reason of the formation of excessive scale on the ingots may be to high temperature in the furnace or a high concentration of oxygen in the furnace atmosphere. This leads to formation of layers of scale, which can be found to be incompletely removed by the scale squeezers. The appearance of the defect may be confused with a husk or the red scale. To avoid the formation of the scale, it is necessary to control compliance with the unloading temperature, the correctness of the operation parameters of the heating furnace of the ingot as well as the efficiency of descaling systems.

## Secondary Scale

The surface of a single defect *(Image 9)* is characterized by a round, black shape with a diameter of 1-2 mm, and a long, white tail directed along the rolling line, which can reach length of up to 200 mm. Defects always appears in groups of different numbers, and white tails can overlap. The defects occur along the entire length of the band, on both sides, with grater severity at the beginning.

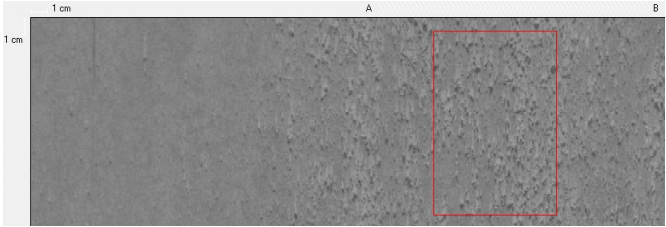


Image 9: Secondary Scale

This type of defect comes from the rolling of scale by a group of finishing frames. Most often it occurs on thin sheets with a thickness below 2 mm at to high rolling temperature. Additional parameters, which causes the creation of defects are low-intensity cooling of rolls and strand as wear of rolls. When the look of the defect is not prolonged, it can be assumed that it was created on one of the middle finishing frames. Defect detection, and classification can be difficult due to defects giving different region of interest (ROI). The defect is erroneously classified as defect which looks like letter *V*. To prevent formation of defect, it is necessary to control compliance with the rolling temperature in the production of thin sheets (below 2 mm) and the parameters of the group of finishing mills, in particular the cooling performance of the rolls. An increase in the occurrence of a defect may indicate a less efficient operation of the descanters of the initial mill and the group of finishing mills.

## Rolled *“V”* scale

Rolled scale which looks like the letter *V* is a kind of defect, which originate from the group of finishing frames *(Image 10)*. Its shape resembles the letter V, which width and height reaches a maximum of 20 mm. Typically, the defect appears in numerous groups, on the upper surface and the beginning of the band, but may appear on its entire length.

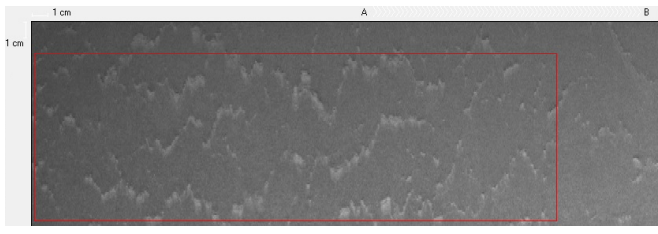


Image 10: V scale

Like the rolled scales, this type of defect comes from the group of finishing frames. Most often it occurs on thin sheets below 2 mm with too high rolling temperature. As in the case of rolled-up secondary scale, additional parameters affecting defects are low-intensity cooling of rolls and strand, and wear of rollers. When the look of defects is not extended, it can be assumed that it was made in one of the middle finishing frames. Additionally, the origin can be related with the chemical composition of steel. Steels containing phosphorus are particularly susceptible to this defect. In order to prevent forming of a defect, it is necessary to control compliance with the rolling temperature in the production of thin sheets, as well as the parameters of the group of finishing mills. Increasing the occurrence of a defect may indicate a less efficient operation of scale desiccation rollers and a group of finishing mills.

## Peeled roll scale

The cause of this defect *(Image 11)* is a slight loss of working roll caused by thermal or mechanical damage of its surface. The other name of this defect is a *black skin scale*. It has an oval shape and consist of small, black points with a diameter a round of 1-2 mm. Defect can occur on both sides of band, along the whole length in characteristics stripes.

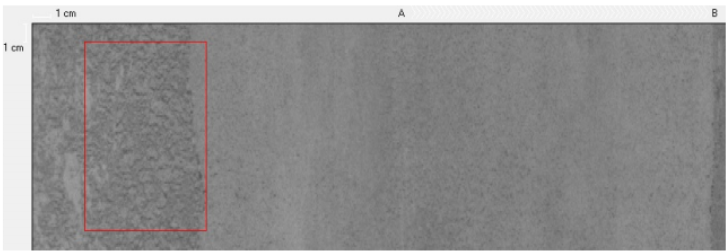


Image 11: Peeled roll scale

The disadvantage usually arises on the first frames of the finishing group. The immediate cause is the wear of the rollers, for example during the rolling long sheet metal of a short length. The appearance of this defect means that the working rolls will have to be sanded. The defect is discovered in large area of ROI. Its classification is sometimes confused with Secondary Scale. In order to avoid forming the defect, it is necessary to control compliance with the rolling temperature in the production of thin sheets, with particular emphasis on maintaining the lowest possible ending temperature of the bands from the group of finishing mills. It is also necessary to monitor the parameters of the group of finishing mills, and in particular to meet the required reduction in band thickness. Increasing the occurrence of a defect may indicate about deterioration of the surface condition of work rolls, or less efficient work of mill scale descaler, and groups of finishing mills.

## Red scale / Tiger scale

According to work (Fukagawa i in., 1994) red scale *(Image 12)* is a type of scale formed due to the high content of silicon in the steel alloy. It is precipitated in the furnace before the rolling process. After rolling, it turns red. The defect consists of long and irregular stripes and has a noticeably greater harshness than the rest of the surface of the strand. Its length reaches several centimetres. It can occur on whole length of band, on the both sides.

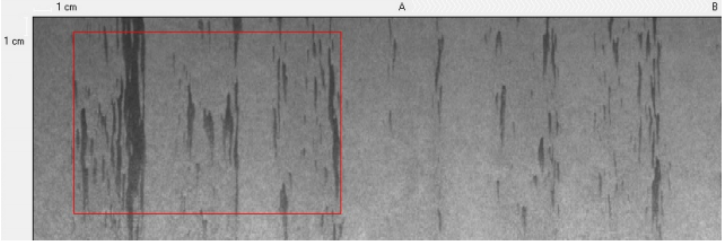


Image 12: Red Scale

Defect appears on steels with a silicon addition in the chemical composition. Usually the defect will be removed during the etching process (Breitschuh i in., 2007). In order to monitor the occurrence of defects, verification of the rolled steel grade should be performed. If it is silicon steel, then check the level and range the presence of scale. If it is not, the chemical composition of steel should be performed in order to verify the correctness of its casting. Defect detection tends to broadcast every large ROI, often covering the entire length and width of a single image. Defect classification can be confused with husks and rolled-in primary scale.

## Heavy scale

Heavy scale *(Image 13)* is intensified variant of rolled-in primary scale, which formation is caused by the improper operation of scale squeezers. The entire ROI area is covered a clear and thick scale. The defect size is between from 500 mm to 2000 mm (on band width) or 20000 mm (on the band length). Its can occur on both sides of band, and it entire length. Numerous clusters of defects can be observed at the beginning of band, or in places where the scaling of the scale started to work incorrectly.

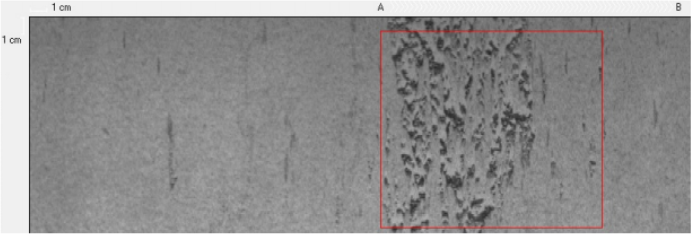


Image 13: Heavy Scale

Defect may appear on all types of steel in the course of improper operation of the scale squeezer. The classification may not be correct, because of the possibility of confusing the defect with the rolled-in primary scale. In order to avoid formation of defect, first of all, the efficiency of scale descaling systems should be controlled. Additional parameters, that may affect the level of defects, there are parameters of heating the ingot in the furnace and the inflated temperature of its unloading.

## Bad descaling

Bad descaling, called also Finishing Scale Breaker (FSB), arises due to damage or abnormal operation of scale squeezers located in front of group of finishing mills *(Image 14)*. It can be composed from the different scales. The nature of this defect clearly indicates to need to stop the rolling process and check the descaling system. The defect has the shape of longitudinal strips of scale, which appear in the places of improper operation of the knockout nozzles. The length of strips is from a few centimetres to even several hundred meters. The width of the defect depends on the number of the number of non-operating nozzles of scale squeezer. Defect can appear on whole length and width of band, on both sides.

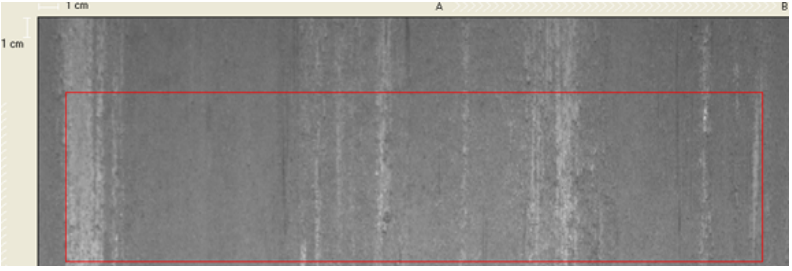


Image 14: Bad descaling

In order to avoid creating a defect, all parameters related to the correct operation of descaling systems located in front of a group of finishing mills should be controlled. In particular, it can be talk about the correctness of the operation of the sensors and automation of pounders, pressure and flow of water on the nozzles of beaters, patency of the nozzle nozzles, and the speed of the rolled stand in relation to the performance of skiners.

According to describe above, bad descaling is defect, which consist of other scales, which have not been properly removed by the pounders. Moreover, the information about the occurrence of this defect does not come from one image, and it could not classified by different decision systems. Therefore, the defect is not a subject to direct classification by AI methods.

# Methods of classification of defects