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PHENOMENOLOGICAL MODEL DESCRIBING THE FORMATION OF PEELING DEFECTS ON HOT-ROLLED DUPLEX STAINLESS STEEL 2205

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The chemical composition, morphology, and microstructure of peeling defects formed on the surface of sheets from steel 2205 under hot rolling are studied. The microstructure of the surface is analyzed using scanning electron and light microscopy. The zones affected are shown to contain nonmetallic inclusions of types Al_2O_3 and $CaO – SiO_2 – Al_2O_3 – MgO$ in the form of streak precipitates and to have an unfavorable content of austenite, which causes decrease in the ductility of the area. The results obtained are used to derive a five-stage phenomenological model of formation of such defects.

Key words: duplex stainless steel 2205, hot-rolled sheets, surface peeling defect, zone of low ductility, phenomenological model.

INTRODUCTION

Duplex (double-phase) stainless steels are novel and promising materials. Their structure consists of austenite and ferrite phases. The unique combination of high strength, toughness, corrosion resistance, weldability and efficiency explain their successful application in various branches of industry and especially in articles operating under extreme conditions, for example, in chlorine-containing environments [1 – 3].

The quality of the surface of articles from duplex steels affects their operating properties very much. We know that advancement of the quality of articles and reduction of rejection raises drastically the efficiency of their production at metallurgical plants. The surface quality of parts has become an object of intense attention and study [4 – 9]. However, the causes of the appearance of various types of defects may differ even for the steel of one grade.

The aim of the present work was to study peeling defects formed on the surface of duplex stainless steel 2205 in the process of hot rolling and to develop a phenomenological model of their formation.

METHODS OF STUDY

We studied hot-rolled sheets from duplex stainless steel 2205 of the following chemical composition (in wt.%): 0.02 C, 21.6 Cr, 5.9 Ni, 2.6 Mo. 0.9 Mn, 0.8 Si, 0.01 S, 0.015 P.

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To determine the causes of formation of surface peeling defects we studied the structure of steel 2205 by scanning electron and optical microscopy. The results of the study were used to develop a phenomenological model of formation of peeling defects on the surface of the steel.

RESULTS AND DISCUSSION

Morphology of the Surface Defect of Hot-Rolled Sheets

A peeling defect on the surface of a hot-rolled sheet is presented in Fig. 1. Such defects are arranged on the surface of the sheet discretely. The length of a defect is about 1 mm; the width is about 1 mm. Conventionally, we may represent this defect in the form of two parts, i.e., a shallow depression formed as a result of local detachment of a peel and a bridge between the peel and the base metal.

To study the morphology of the defect in cross section, we cut a hot-rolled sheet so that the line of the cut passed through the middle of the defect over the rolling direction. The structure of the specimen is presented in Fig. 2*a*. It can be seen that a long microcrack has formed between the detached part of the peel and the base metal. In the extreme left-hand position of the defect we can observe detachment from the base metal. In the middle of the defect we can see microscopic discontinuities (bulges), where the metal has obviously been foliated.

Figure 2*b* presents an image of the defect in a coordinate system where axis *X* goes along the length of the defect and axis *Y* goes over the thickness of the sheet. The thick black broken line depicts the contour of the defect and the under-

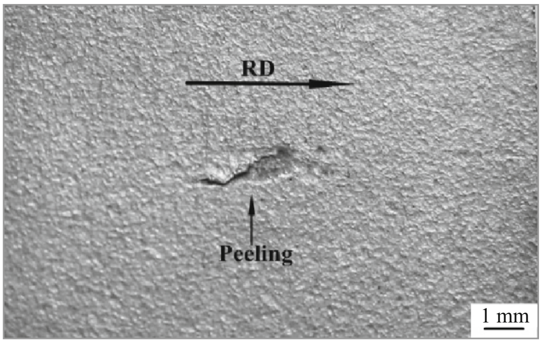

Fig. 1. A peeling defect on the surface of a hot-rolled sheet from steel 2205 (RD is the rolling direction).

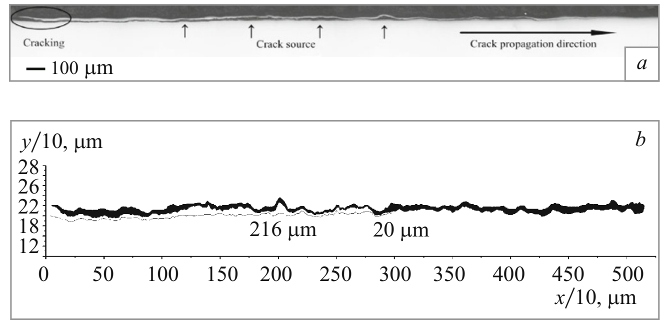

Fig. 2. Morphology of a peeling defect in longitudinal section of a rolled sheet from steel 2205 (unetched specimen, optical microscopy) (*a*) and its graphical representation in cross section of the sheet (*b*) (126 μm is the maximum thickness of the defect; 20 μm is the minimum thickness).

neath light-gray line depicts the contour of the base metal. In accordance with the graphical representation the defect may be described by the following parameters. The total length of the defect is 5103 μm. The length of the subsurface part of the defect (the left-hand part of the image) is 2980 μm; the thickness of the defect (the distance between the lower gray line and upper black line, i.e., between the boundary of the base metal and the bottom of the subsurface defect) varies from 20 to 216 μm.

Microscopic bulges appear on the region from 1000 to 3000 μm (Fig. 2*b*), and the contour of the defect has a wavy pattern. This may be connected with the appearance of tensile stresses directed perpendicularly to the surface of the rolled metal. Formation of tensile stresses in the zone of reduced ductility of the metal can cause local fracture, i.e., formation of a microcrack in the regions of active formation of waves. Further development of the microcrack should cause larger-scale foliation, which corresponds to the contour on the region from 0 to 1000 μm (Fig. 2*b*); later on the foliated part of the metal will be detached, which will be observed on the surface of the rolled sheet.

Analysis of Energy Spectra in the Zone of Defect

We analyzed the energy spectra of the defect on a longitudinal specimen using a scanning electron microscope. The morphology of the defect is presented in Fig. 3. We observe nonmetallic inclusions in the form of streak precipitates between the defect and the base metal. The results of the analysis of their energy spectra are presented in Table 1. The inclusions contain Mg, Ca, Al, Si, O and other elements. Such elements enter nonmetallic inclusions of types Al_2O_3 and $CaO – SiO_2 – Al_2O_3 – MgO$. Accumulation of such inclusions may give rise to micro- and macrofractures in the process of hot rolling due to the reduced ductility of the metal in these zones. Thus, streak precipitates of nonmetallic inclusions may be the most important factor for the appearance of surface defects of the peeling type. In the process of hot rolling such nonmetallic inclusions are chiefly arranged over the direction of the deformation, i.e., in parallel to the surface of the rolled sheet.

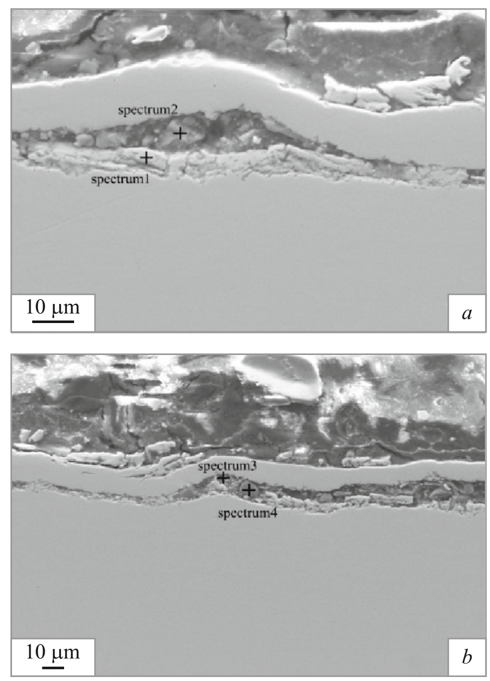

Fig. 3. Structure of the surface layer of a rolled sheet from steel 2205 in the region of a peeling surface detect with points of analysis of energy spectra *1*, *2*, *3*, *4* obtained under a scanning electron microscope.

Microstructure in the Zone of Defect

The microstructure in the zone of the defect is presented in Fig. 4. According to the results of the evaluation of the volume fractions of the structural components, the content of austenite is 58.5% and that of ferrite is 41.5%. This proportion of structural components is not optimum for hot deformation. It is known that in hot rolling of a billet, strain develops under the conditions of existence of a double-phase region, i.e., austenite and ferrite. If the proportion of the structural components is not optimum, for example, at an elevated content of austenite, the straining of the austenite and of the

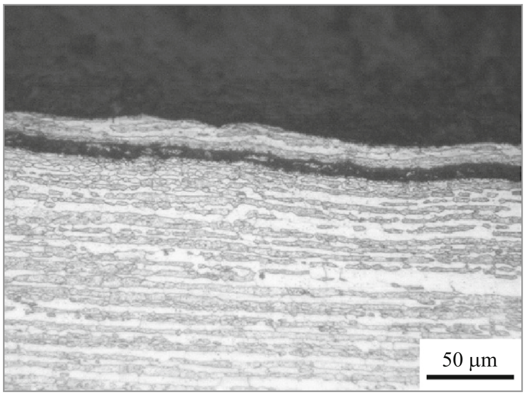

Fig. 4. Microstructure in the zone of a peeling surface defect on steel 2205.

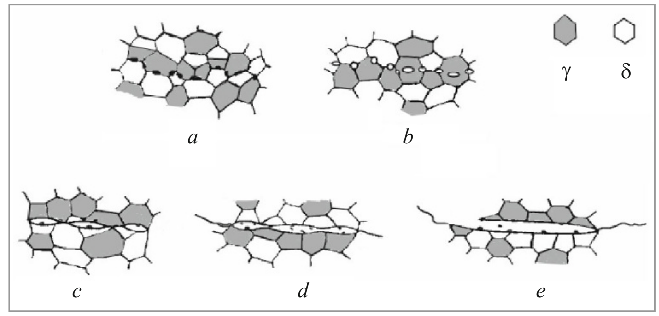

Fig. 5. Scheme of the phenomenological model of formation of defect: *a*) appearance of a zone of low ductility; *b*) nucleation of microcracks; *c*) growth of microcracks; *d*) propagation of microcracks; *e*) formation of peeling defect on the surface of rolled metal.

ferrite is hardly coordinated. This may reduce the capacity of the steel for hot plastic deformation, i.e., may give rise to a microcrack at the austenite/ferrite interface. Thus, the interface of the two phases may also be a zone of reduced ductility of the metal and the second cause of the appearance of a peeling defect on the surface. In hot rolling, the boundary between the austenite and the ferrite is also arranged over the direction of the principal strain and in parallel to the surface of the rolled article.

Phenomenological Model of Formation of Defect

The results described were used to develop a phenomenological model of formation of a peeling defect, which is presented schematically in Fig. 5. The process of formation of such defect may be divided into the following five stages.

1. Appearance of zones of low ductility in the metal. Such zones contain accumulations of nonmetallic inclusions and phase boundaries near which the content of austenite is not optimum from the standpoint of formation of high process ductility (Fig. 5*a*).

2. Appearance (nucleation) of microcracks. In the zones of low ductility, the strength of cohesion between nonmetallic inclusions and the base metal or austenite and ferrite is reduced, which creates conditions for easy nucleation of microcracks, as it is shown in Fig. 5*b*.

3. Growth of microcracks. In the general case microcracks are located discretely. In the case of a tensile stress under rolling, which is perpendicular to the surface of the rolled metal, the microcracks may grow and acquire an oval shape, as in Fig. 5*c*. Individual microscopic bulges appear on the surface of the rolled metal on the corresponding area.

4. Propagation of microcracks. Due to the parallel arrangement of microcracks with respect to the zone of low ductility, they propagate easily over the direction of the deformation, as a result of which the defect is detached from the base metal as is shown in Fig. 5*d*.

5. Formation of a peeling defect on the surface of the rolled metal (Fig. 5*e*).

CONCLUSIONS

1. Peeling surface defects appear discretely on the surface of hot-rolled sheets from stainless steel 2205. Such a defect has the form of a microscopic bulge with one end detached from the surface of the rolled metal and the other end attached to the base metal.

2. The main cause of formation of a peeling surface defect is appearance of a zone of low ductility in the form of streak precipitates of nonmetallic inclusions of types Al_2O_3 and $CaO - SiO_2 - Al_2O_3 - MgO$ and phase boundaries near the regions with nonoptimal content of austenite (58.5 %).

3. A phenomenological model has been developed. In accordance with the model, the process of formation of a peeling defect on the surface may be broken into 5 stages,

TABLE 1. Results of the Analysis of Energy Spectra

Spectrum	Content of elements, wt.%							
	Fe	Cr	Mo	O	Mg	Al	Si	Ca
1	55.91	–	0.16	30.27	2.62	2.00	7.44	1.60
2	60.33	–	–	33.72	1.51	4.44	–	–
3	65.39	8.76	–	23.47	–	–	–	2.38
4	1.20	–	–	45.89	–	52.91	–	–

Note. The location of the points of the analysis of spectra *1* – *4* is presented in Fig. 4.

namely, appearance of a zone of low ductility, nucleation of microcracks, growth of microcracks, propagation of microcracks, and formation of a peeling defect on the surface of rolled metal.

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