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THE EFFECT OF COILING TEMPERATURE ON CHARACTERISTICS OF CONTINUOUSLY CAST LOW-CARBON STEEL

UTICAJ TEMPERATURE NAMOTAVANJA NA OSOBINE KONTINUIRANO LIVENOG NISKOUGLJENIČNOG ČELIKA

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ABSTRACT

Continuously cast Al-killed low-carbon steel was coiled at low (570 ^{0}C) and high (760 ^{0}C) temperatures. The structures of the steel after coiling at low and high temperatures as well after cold rolling and annealing were investigated. Depending on processing conditions continuously cast Al-killed low-carbon steel exhibits different microstructure and properties. Steel coiled at low temperature after cold rolling and annealing is characterized by pane-cake grains and shows excellent drawability (R=1.7), but due to high hydrogen permeability (t_od^{-2}=6min mm^{-2}) its resistance to fishscaling is rather low. The microstructure of steel coiled at high temperature contains polygonal grains and fragmented carbides which are a prerequisite for low hydrogen permeability (t_od^{-2}=46min mm^{-2}) and good resistance to fishscalling.

Key words: Continuously cast Al-killed low-carbon steel, deep drawing, enameling, hydrogen permeability, fishscaling.

IZVOD

Kontinuirano liven niskougljenični čelik umiren aluminijumom je posle toplog valjanja namotan na različitim temperaturama u cilju ispitivanja strukture i osobina. Čelik namotan na niskoj temperaturi (570 ^{0}C) posle hladnog valjanja i žarenja karakteriše izduženo zrno i odlična sposobnost oblikovanja dubokim izvlačenjem (R=1.7). Usled viske propustljivosti za vodonika (t_od^{-2}=6min mm^{-2}) ovaj čelik je sklon stvaranju greske na emajliranim površinama poznate po nazivu riblja krljušt pa nije pogodan za emajliranje. Mikrostruktura čelika koji je namotan na visokoj temperaturi (760 ^{0}C) se sastoji od poligonalnih zrna i zdrobljenih čestica karbida u čijoj se okolini nalaze mikropukotine čije je prisustvo preduslov za malu propustljivost za vodonik (t_od^{-2}=46min mm^{-2}) i visoku otpornost prema stvaranju riblje krljušti.

Ključne reči: Kontinuirano liven niskougljenični čelik umiren Al, duboko izvlačenje, emajliranje, propustljivost za vodonik, riblja krljušt.

INTRODUCTION

Compared to classic cast steels continuously cast steels possess many advantages not only in the production economy, but also when the quality is of the primary interest. The main characteristic of continuously cast steels is their capacity for deep drawing. In the car industry, which is one of the biggest consumers of steel sheets, continuously cast steels completely replaced non-killed steels. The same situation exists when the deposition of different coatings like enamels concerned. However, due to their marked tendency toward fishscaling, *i.e.* a defect that appears as small half-moon shaped fractures, somewhat resembling the scales of a fish, these steels were not suitable for the classical enameling. After enamel baking and during the subsequent process of cooling fishscale may be formed by bursting of enamel due to the pressure of hydrogen developed at the interface metal-enamel [1]. The formation of fishscale is strongly related to the hydrogen content dissolved in enameling sheets during enamel firing. In general, the decrease of hydrogen permeability increases the fishscale resistance of enameled products. The appearance of fishscaling may be successfully eliminated if the process of cold rolling is applied following hot rolling and high temperature coiling. The coarse particles of carbides (cementite) present in the metal matrix are fragmented and cracked when the high degree of cold reduction is applied. It was found that traps strongly influence hydrogen solubility and diffusivity in steels [2]. Vacancies, dislocations, interfaces and microvoids can be considered as possible trapping sites. Microvoids formed at the interface between fragmented carbide particles and the matrix serve as sites where hydrogen atoms diffuse and combine into molecules which are then trapped and unable to cause any defect [3]. To prevent the precipitation of aluminum from the solid solution continuously cast Al-killed low-carbon steel for deep drawing after hot rolling should be coiled at low temperatures. During heating of the cold rolled steel to the annealing temperature AlN precipitates from the solid solution. It is important that the heating rate is sufficiently low (less than 50 ^{0}C/h) [4] in order to attain some degree of recovery before fine AlN particles precipitate at grain and subgrain boundaries promoting development of a strong (111) texture. This texture corresponds to the generation of characteristic elongated grains, the so called pane-cake structure [5]. The morphology of this structure ensures good ability of steel to deep drawing.

The objective of this paper was to study the effect of coiling temperature on the microstructure, drawability and resistance to fishscaling of continuously cast Al-killed low-carbon steel.

EXPERIMENTAL

Two procedures for production of continuously cast Al-killed low-carbon steel either for deep drawing (steel coiled at low temperature and annealed – LCT) or enameling (steel coiled at high temperature and designated as HCT in the further text) are applied and their parameters are schematically presented in Table I. The chemical analysis of steel is given in Table II.

Table I. Schematic presentation of two procedures for production of continuously cast Al-killed low-carbon steel for deep drawing or enameling applications.

Tabela I Šematski prikaz postupka za dobijanje kontinuirano livenog niskougljeničnog čelika pogodnog za duboko izvlačenje i emajliranje.

<table>
<tr><td colspan="2">CONTINUOSLY CAST Al-KILLED STEEL LOW-CARBON</td></tr>
<tr><td colspan="2">⇓</td></tr>
<tr><td colspan="2">HOT ROLLING</td></tr>
<tr><td colspan="2">⇓</td></tr>
<tr><td>COILING AT LOW TEMPERATURE (570 ^{0}C)
(Al and N remain in solid solution)</td><td>COILING AT HIGH TEMPERATURE (760 ^{0}C)
(Massive carbides are formed)</td></tr>
<tr><td>⇓</td><td>⇓</td></tr>
<tr><td>COLD ROLLING</td><td>COLD ROLLING
(High degree of cold reduction, massive carbides are cracked and fragmented)</td></tr>
<tr><td>⇓</td><td>⇓</td></tr>
<tr><td>ANNEALING
(Low heating rate, AlN precipitates during recovery)</td><td>ANNEALING</td></tr>
<tr><td>⇓</td><td>⇓</td></tr>
<tr><td>SUITABLE FOR DEEP DRAWING APPLICATIONS</td><td>SUITABLE FOR ENAMELING APPLICATIONS</td></tr>
</table>

Table II. The chemical analysis of continuously cast Al-killed low-carbon steel.

Tabela II. Hemijska analiza kontinuirano livenog niskougljeničnog čelika umirenog Al.

Content of elements, wt.%						
C	Si	Mn	P	S	Cu	Al
0.04	0.03	0.02	0.19	0.18	0.04	0.04

The microstructure of treated steels was examined by light microscope “Zeiss Axiovert 25” and scanning electron microscope (SEM) “JEOL 35”. Polishing was performed using the standard procedure, whereas a Nital and Picral reagents were used for etching. The hydrogen permeability was calculated using the relation ($t_o d^{-2}$) [6], where t_o is time necessary for the hydrogen to diffuse through the whole thickness, d, of the sheet. t_o was measured on the polished sheet using the “Hyperm” instrument composed of electrolytic cell where hydrogen is developed through an electrochemical reaction in a diluted sulphuric acid solution, which utilizes the sample as a cathode. Hydrogen passes through the sample and is detected by the flux sensor. The steel is capable for enameling when t_od^{-2} values are higher than 8 min mm^{-2}. The higher t_od^{-2} value means lower hydrogen permeability, *i.e.* higher resistance of steel to fishscaling. The drawability was measured by an average plastic strain ratio, R, as well as the texture development. The R value and the relative intensities of five different reflections (110), (200), (210), (310) and (222) were determined following the procedure described in a previous paper [7].

RESULTS AND DISCUSSION

The microstructure of LCT and HCT steels after annealing is shown in Figs. 1 and 2, respectively. The characteristic elongated grains (pan-cake structure) dominate the structure of LCT steel (Fig. 1a,b). On the other side, the microstructure of HCT steel mainly consists of polygonal grains (Fig. 2a) with some microvoids present at the grain boundaries (Fig. 2b). These microvoids originate from previously formed carbides.

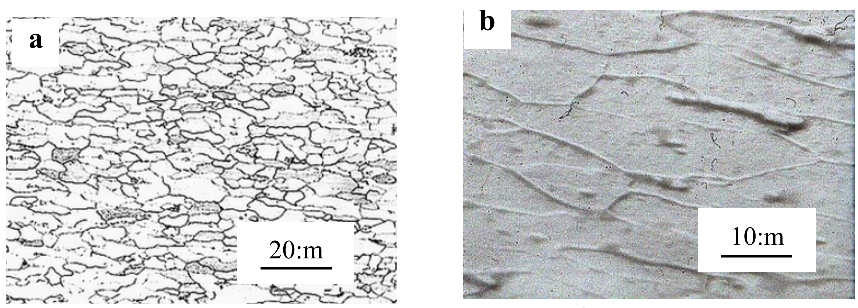

Figure 1. Microstructure of steel coiled at 570 ^{0}C after annealing:
a. Light micrograph; b. SEM micrograph.

Slika 1. Mikrostruktura čelika namotanog na 570 ^{0}C u žarenom stanju:
a. Svetlosna mikroskopija; b. Skenirajuća elektronska mikroskopija.

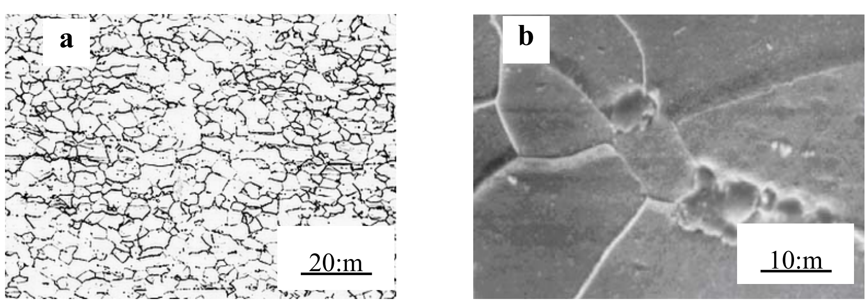

Figure 2. Microstructure of steel coiled at 760 ^{0}C after annealing:
a. Light micrograph; b. SEM micrograph.

Slika 2. Mikrostruktura čelika namotanog na 760 ^{0}C u žarenom stanju:
a. Svetlosna mikroskopija; b. Skenirajuća elektronska mikroskopija.

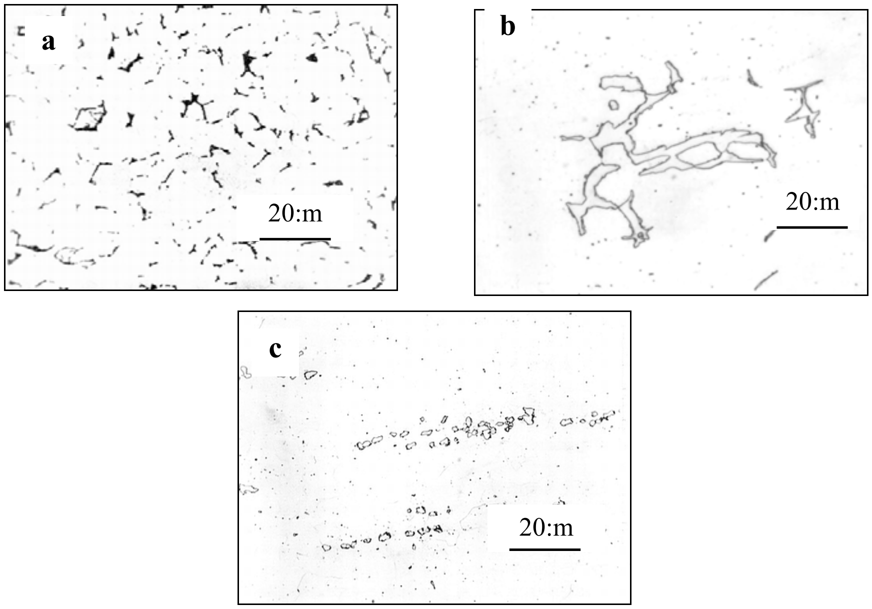

Figure 3. Light micrograph. a. Carbides in steel formed after coiling at 570 ^{0}C; b. massive carbides formed in steel after coiling at 760 ^{0}C; c. massive carbides in HCT steel fragmented into smaller particles after cold rolling

Slika 3. Svetlosna mikroskopija. a. karbidi obrazovani u čeliku posle namotavanja na 570 ^{0}C; b. krupni karbidi obrazovani u čeliku posle namotavanja na 760 ^{0}C; c. krupni karbidi zdrobljeni posle hladnog valjanja

Morphology of carbides in LCT and HCT steels is shown in Fig. 3a-c. Fig. 3a illustrates small grain boundary carbides in LCT formed after coiling at the low temperature, contrary to massive carbides formed in HCT steel during coiling and before cold rolling (Fig. 3b). After cold rolling massive carbides in HCT steel are fragmented into smaller particles (Fig. 3c). Fragmented carbide particles and microvoids may be clearly seen in the microstructure of the HCT steel (Fig. 4a,b), as well as microvoids left from carbides pulled out during the metallographic preparation of the specimen (Fig. 4c). Microvoids formed at the interface between fragmented particles of carbides and the matrix serve for hydrogen trapping and decrease hydrogen permeability.

Table III. The effect of coiling temperature on relative intensities of reflections of continuously cast Al-killed low-carbon steel.

Tabela III. Uticaj temperature namotavanja na relativan intenzitet refleksija kontinuirano livenog niskougljeničnog čelika umirenog Al.

Coiling temp., ^{0}C	Relative intensity of reflection				
	(110)	(200)	(210)	(310)	(222)
570	0.58	1.00	1.90	0.80	4.60
760	0.60	2.68	1.11	0.72	0.81

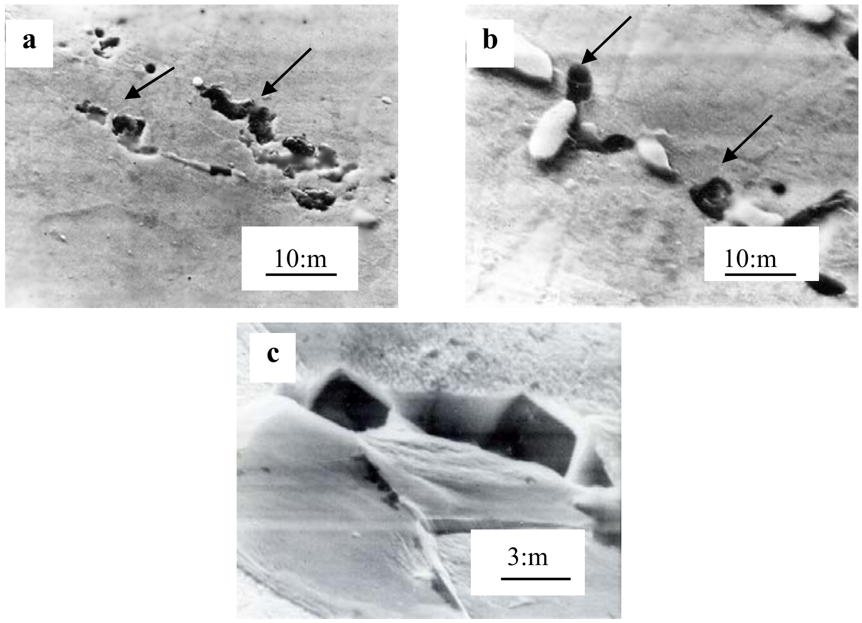

Figure 4. SEM micrograph of HCT steel. a, b Fragmented carbide particles and microvoids (denoted by arrows); c. microvoids.

Slika 4. Skenirajuća elektronska mikroskopija. Čelik namotan на 760 ^{0}0. a, b. zdrobljene čestice karbida i mikropukotine (označeni strelicama); c.mikropukotine.

The hydrogen permeability and R value of the HCT steel were 46min mm^{-2} and 1.12, respectively, whereas for LCT steel R value was 1.7, but the hydrogen permeability was only 6min mm^{-2}. Table III shows relative reflection intensities as a function of coiling temperature. In the microstructure of HCT steel the most pronounced is (200) reflection, whereas in LCT steel mostly favored are (222) and (210) reflections which increase the ability to deep drawing. Comparing intensity values, it is evident that LCT steel has excellent drawability, but due to the high hydrogen permeability it possesses lower resistance to fishscaling. In the case of HCT steel the situation is quite opposite, *i.e.* this steel is quite suitable for enameling.

CONCLUSION

Depending on processing conditions continuously cast Al-killed low-carbon steel exhibits different microstructure and properties.

- The pan-cake microstructure and increased relative intensities of (222) and (210) reflections indicate excellent drawability (R=1.7) of steel coiled at low temperature (570 ^{o}C), but due to the high hydrogen permeability ($t_o d^{-2}$=6min mm^{-2}) the resistance of this steel to fishscaling is rather low, *i.e.* it is not suitable for enameling applications.

- Steel coiled at high temperature (760 ^{o}C) has good resistance to fishscalling as a consequence of hydrogen trapping at the interface between fragmented carbides and the matrix whereby the hydrogen permeability ($t_o d^{-2}$=46 min mm^{-2}) of this steel is reduced.

Acknowledgments

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