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A ROLL'S WEAR DURING HOT ROLLING OF HIGH-SILICON STEEL AND ITS IMPACT ON THE QUALITY OF A STRIP'S PROFILE

ZUŻYCIE WALCÓW ROBOCZYCH W PROCESIE WALCOWANIA STALI WYSOKOKRZEMOWYCH I JEGO WPŁYW NA JAKOŚĆ WALCOWANEJ BLACHY

Key words: hot rolling, high-silicon steel, work rolls wear, quality defects (strip profile deformation).

Abstract: Hot rolling of grain-oriented high silicon steel is related to technical problems such as high temperature and long rolling campaigns with strips of the same width. Numerous methods may be carried out as a solution to these problems. Before the rolling campaign, all rolls of finishing stands are exchanged. The campaign is scheduled with additional exchanges of rolls on two last stands in two stages. A roll's wear increases with the quantity of rolled material and may lead to strip profile deformation. Exchanging the rolls ensures the required steel quality and prevents losses caused by quality defects. This work identifies factors affecting the work roll's wear and refers to the material from which rolls are made. This work aimed to determine the wear of work rolls of the finishing group rolling mills during the rolling of high-silicon steel. The work presents wear analyses of 30 rolls. It was analysed depending on roll type and high silicon steel rolled material quantity. Compared wear of rolls after rolling high-silicon steel and black sheet. By analysing the distribution of roll wear along the length of the roll, it was found that the wear of working rolls directly affects the geometry of the rolled sheet, which may affect the quality of the strip profile of the rolled sheet.

Słowa kluczowe: walcowanie na gorąco, stale wysokokrzemowe, zużycie walców, wady jakościowe.

Streszczenie: Walcowanie stali wysokokrzemowych o zorientowanym ziarnie wiąże się z problemami technologicznymi takimi jak: wysoka temperatura walcowania i bardzo długa sekwencja walcowania blachy o tej samej szerokości. Rozwiązanie tych problemów prowadzone jest wieloaspektowo. Przed rozpoczęciem procesu walcowania stali wysokokrzemowych następuje wymiana walców roboczych we wszystkich walcarkach wykańczających. Walcowanie planowane jest z przebudową pośrednią walców roboczych, w dwóch ostatnich walcarkach. Po odwalcowaniu określonej ilości materiału konieczne jest wycofanie narzędzi do regeneracji z uwagi na postępujące zużycie walców roboczych. Przebudowa pośrednia walców ma na celu zapewnienie wymaganej jakości blachy i niedopuszczenie do strat związanych z powstawaniem wad jakościowych. Niniejsza praca określa czynniki wpływające na zużycie walców, odnosząc je również do materiału, z którego wykonane są narzędzia. Celem pracy było określenie zużycia walców roboczych walcarek grupy wykańczającej podczas walcowania stali wysokokrzemowej. W pracy przedstawiono analizę zużycia 30 walców roboczych. Analizowano zużycie w zależności od rodzaju walca podczas walcowania stali wysokokrzemowej, porównano zużycie walców na poszczególnych klatkach walcowniczych w zależności od ilości przewalcowanej stali wysokokrzemowej, dokonano porównania zużycia walców po walcowaniu stali wysokokrzemowej i walcowaniu blachy czarnej. Obserwowany nierównomierny rozkład zużycia walców na ich długości może wpływać na kształt walcowanej blachy, co może przekładać się na jakość profilu poprzecznego.

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INTRODUCTION

High-silicon grain-oriented steels containing about 3% Si are widely used in the electrical engineering industry. Magnetically soft materials with high magnetic permeability and low loss along the rolling direction are used for transformer and generator cores **[L. 1]**. Despite a long history of continuous improvement in production routes, dating back to 1934 when Goss invented the process for making this type of steel, to this day, based on obtaining the so-called Goss structure, there is still space for further improvement in its manufacturing processes. Hot rolling of steel is one of the initial stages, but like any other manufacturing process, it plays an important role in producing the final product. Even at the initial stage of hot rolling, this type of steel requires a strictly defined time of reheating the slabs to high temperatures of 1150–1300°C **[L. 2]**. The entire rolling process is carried out at significantly higher temperatures than the rolling process of classic low-carbon steel, with reduced cooling at each stage. At this stage, selecting the right temperatures is particularly important since the size of the precipitates formed significantly impacts the recrystallisation process, as one of the subsequent production stages of electrical steel **[L. 3]**. The length of the rolling campaign and the temperature influence the work rolls' abrasive wear, while the work rolls' surface area significantly affects the product's quality **[L. 4]**. When contact is made between the rough yet hot surface of the steel and the work rolls, the latter is subjected to wear. Hot-rolled steel heats the work rolls' surfaces, increasing their temperature. The rotating rolls undergo periodic temperature oscillations, cyclical thermal stresses, and strains. The thermal stresses on the roll surfaces are usually comparable to or even greater than the mechanical stresses, especially in the early finishing stands where the rolled strip temperatures and the temperature gradients are higher **[L. 5].** In order to reduce a rise in temperature of the rolls, water cooling is used, which, as mentioned earlier, is significantly limited while rolling high-silicon steels. Maximum surface temperatures of the work rolls during rolling are 500-700°C, while minimum temperatures are between 100°C and 200°C during water cooling **[L. 6].** The rolling schedule is a particularly difficult task, as it requires considering many constraints, such as the temperature to which slabs are reheated in the furnace, the principles of the rolling campaign (starting from wide to narrow widths), and the work rolls exchange. Work rolls must be exchanged periodically due to their progressive wear during rolling, affecting the rolled strip's quality. Rolls removed from the stand are turned to recondition, which is done by grinding the surface of the rolls. In order to reduce grinding operations, the aim is to roll as much material as possible on one set of rolls. It is estimated that exchanges and premature wear of work rolls can account for up to 15% of production costs. **[L. 7, 8]**. In the rolling process of high-silicon steel, the rules for scheduling the rolling campaign are more demanding, and the frequency of roll changes is increased. Long rolling sequences of material of the same width and high rolling temperatures at all stages of the process impact the wear of the work rolls and consequently impact product quality. Rolling a large amount of material in one width causes uneven wear of the rolls, which creates additional difficulties in maintaining a high-quality thickness cross profile of the rolled strip. This results in quality defects such as deformation of the thickness cross profile, in the form of so-called "cat ears". As a solution to this problem, various methods of work rolls shifting control are used, described in the literature as CVC (continuously variable crown), ASR (asymmetry self-compensating rolling) – technology involving asymmetrical grinding of the rollers, or conventional K-WRS (Kawasaki Steel Work-Roll Shifting) – technology that can result in dispersed and even wear on the work rolls thanks to the symmetrical contour of the rolls **[L. 9, 10].** Considering the numerous limitations and requirements for rolling high-silicon steels described above, high temperatures raise the need to verify the wear rate on work rolls. This study aimed to determine the wear of work rolls after a rolling campaign of high-silicon steel, taking into account the type of material from which the rolls are made.

EQUIPMENT AND MEASUREMENTS

The subject of the study was to determine the amount of wear on the work rolls. The wear of work rolls in the finishing mills after they have been removed for grinding was studied. Each work roll's diameter was measured before and after the grinding operation. The grinding aims to reproduce the desired shape of the barrel of the rolls, which is essential for the proper rolling process. The diameter was measured using a measuring tower equipped with two arms – an upper arm and a lower arm. During the measurement, the tower moves along the barrel of a slowly rotating roll in the grinder. At this time, the arms are in contact with the surface of the rolls from the bottom and top. The continuously measured distance between the arms of the measuring tower is then converted into the diameter of the work rolls. The wear of a work roll in one rolling campaign is the difference between its diameter after grinding measured before and after the campaign. The finishing mills have three types of work rolls, each comprising a core and shell. All work rolls have a core with a similar chemical composition but differ in the type of material from which the shell is made. **Table 1**. shows the chemical compositions of the work rolls with reference to the number of the rolling stand in which they are used.

Among all three types of work rolls, HSS (high-speed steels) are characterised by the highest hardness, tensile strength and the greatest resistance to thermal fatigue **[L. 11].** The development of HSS in the early 1990s enabled Hi-Cr (high-chromium) steel work rolls to be progressively substituted in the early finishing stands. However, it could not be

Table 1. Cast chemical composition of work rolls of finishing mills
Tabela 1. Wytopowe składy chemiczne walców roboczych walcarek grupy wykańczającej

Number of stand from which rolls come	Type of roli shell	Chemical composition (wt%)							
		C	Si	Mn	Cr	Ni	Mo	V	Fe
F1-F3	HSS	2.0	0.8	0.6	6.3	0.5	4,0	5,1	Bal.
F4	HiCr	3.0	0.4	1.3	18.0	1.4	1.3	0,3	Bal.
F5-F6	IC	3.0	0.8	1.0	1.8	4.3	0,3	-	Bal.
Core FM		3.3	2.2	0.3	<0.2	0.5	<0.2	-	Bal.

Table 2. Research material origin, quantity, and purpose of the study
Tabela 2. Materiał badawczy – pochodzenie, ilość, cel badania

Length of rolling campaign	**Total quantity of rolled Steel (Iow carbon Steel + high-silicon Steel) [t]**	**Number of work rolls analyzed**	**Aim of the study**
35 cails of high-silicon Steel - Iow zarbon Steel initial 1'40 cails]	1703	12	Comparison of roirs wear distribution on indiwidual stands
72 cails af high-silicon Steel + Iow zarbon Steel initial (40 cails)	2500	4	Comparison cf the wear distribution cf the F4 and F5 work rolls in relation to the amount of materiał
75 coils Iow carbon Steel	1800	5	Determination af wark roIPs wear during rolling cf law carbon steels
72 cails af high-silicon Steel + Iow zarbon Steel initial (40 cails) - wear of work rolls before exch=nging after rolling 50 cails	2000	2	Determination cf wear of work rolls from stand F5 after rolling 50 coils of high-silicon Steel
72 cails of high-silicon Steel + Iow zarbon Steel initial (40 coils) - wear cf work rolls before exch=nging after rolling 25 coils	500	2	Determination of wear of work rolls from stand F5 after rolling 25 coils of high-silicon Steel following work rolfs exchanges (rolling high-silicon Steel only)
72 coils of high-silicon Steel - Iow zarbon Steel initial (40 coils) - wear af work rolls before exchanging after rolling 25 coils	500	2	Determination cf wear of work rolls from stand F6 after rolling 25 coils of high-silicon Steel following the first rclhs exchanges (rolling of hign-silicon Steel only)
72 coils of high-silicon Steel + Iow carbon Steel initial (40 coils) - wear of work rolls before exchanging after rolling 25 coils	500	2	Determination of wear of work rolls from stand F6 after rolling 25 coils of high-silicon Steel following a sezond work rolls exchanges (rolling only high-silicon Steel)

successfully achieved by replacing IC (indefinite chill) rolls in the later stands due to increased cobbles, double-folded strip and tail end pinches. It has been observed that the mechanical cracks of the work rolls used in later stands are deeper in HSS work rolls than in IC work rolls. In addition, a disadvantageous phenomenon eliminating their use in this group of stands is the emerging effect of the strip sticking to the work rolls during the hot rolling of steel **[L. 12]**. The abovementioned issues can be linked to the lower thickness of the rolled material and the higher speed of the work rolls in the last stands. As a result of the analyses carried out in the hot strip mill, it was observed that while rolling the same amount of material, the IC work rolls wear the most (**Fig. 1**). This paper presents the results of a wear analysis of 30 selected work rolls, from three different rolling campaigns. The wear of 12 work rolls from stands F1 to F6 was measured after rolling 1000 t (approximately 40 coils) of low-carbon steel and 700 t (35 coils) of high-silicon steel. Wear of 4 work rolls from stands F5 and F6 was measured after rolling 1000t of low-carbon steel and 1500t (72 coils) of high-silicon steel, wear of 6 work rolls from stands F4 -F6 was measured after rolling 1800 t (75 coils) only low-carbon steel. The roll's wear was also investigated after roll exchanges during a campaign consisting of 72 coils of high-silicon steel after rolling 50 and 25 coils.

The results of the analyses are summed up in graphs. The amount of rolled material in tonnes is converted to the number of coils of similar weight and strip length. Comparisons were made between roll's wear within one rolling campaign for high-silicon steel, depending on the roll type. Hi-Cr

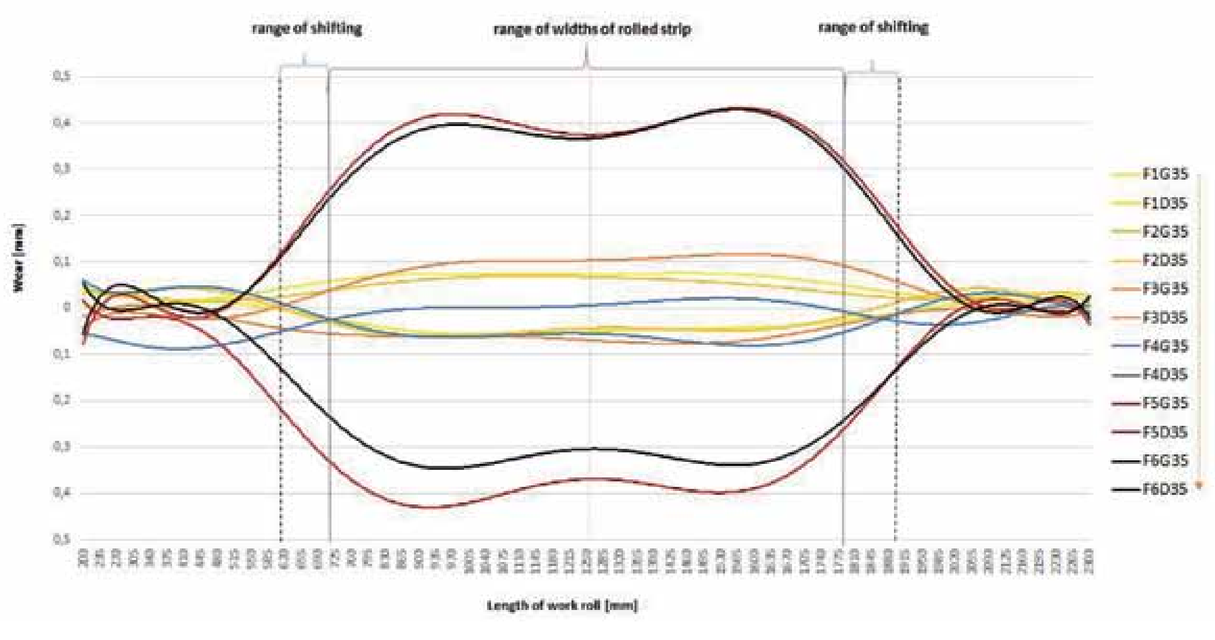

Fig. 1. Wear of work rolls after rolling campaign 35 coils of high-silicon steel in the particular stands

Rys. 1. Zużycie walców roboczych po kampanii walcowania 35 kręgów stali wysokokrzemowej na poszczególnych klatkach walcowniczych

and IC roll's wear was compared depending on the amount of rolled material for high-silicon steel and the roll's wear after rolling low-carbon steel. The measurements and distribution of abrasive wear were recorded with an electronic measuring sensor located in the measuring tower during the grinding of the work rolls after the rolling campaign according to the methodology described at the beginning of this section.

RESULTS AND DISCUSSION

In the diagrams below, the following designations have been adopted: F1–F6 – numbers of stands, G – top roll, D – bottom roll, 35, 50, 72, and 75 number of rolled coils of high-silicon steel. The wear of the IC-type work rolls used in stands F5–F6, is almost four times that of the rollers of stands F1–F4 **(Fig. 1)**. When analysing the effect of wear on the quality of the rolled strip, the distribution of roll wear over the length of the roll's barrel is significant too. Wear on the work rolls is greatest in its central part and gradually decreases in the direction from the centre of the barrel to its edge. This is related to shifting rolls and the arrangement of the strip widths in the rolling campaign. Consequently, this impacts the quality of the rolled strip and, in the case of excessive, uncontrolled wear, can lead to a deformation of the thickness cross profile, which can be seen in the profile diagram as a so-called "cat's ear". **Fig. 2**.

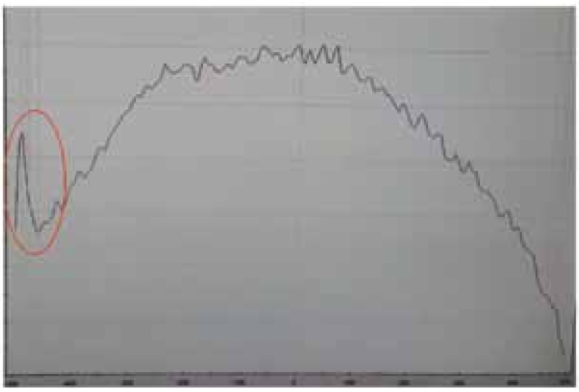

Fig. 2. Thickness cross profile of high-silicon steel strip with the “cat ear” deformation

Rys. 2. Deformacja profilu poprzecznego pasma stali wysokokrzemowej z zaznaczeniem tzw., kociego ucha”

During the rolling of high-silicon steels, the work rolls operate under much more difficult conditions than in the rolling of low carbon steel, when the rolling temperatures are lower and available methods of cooling the work rolls and the rolled strip can be used. Comparing the wear of the work rolls of finishing mills when rolling low-carbon steel (**Fig. 3**) to the wear of the work rolls when rolling high-silicon steel (**Fig. 1**), a more even and flattened wear distribution over the length of the roll barrel is observed. This is because, before each rolling campaign of high-silicon steel, approximately 40 coils of low-carbon steel are rolled (necessary to ensure a sufficient reheating time of the slabs in the furnace); the quantities of rolled material shown in **Fig. 1** and **Fig. 3** are comparable. By comparing the two graphs, it can be seen that for a comparable amount of rolled material, the F6 work rolls wear twice as much when rolling low-carbon steel. The upper work roll of F5 shows similar wear values, the lower work roll of F5 shows slightly less wear, and the lower work roll of F4 wears more. The greater wear of the lower F4 work rolls when rolling low-carbon steel may be due to the higher load forces compared to high–silicon steel.

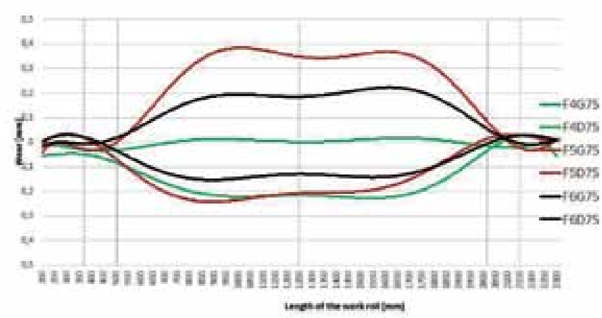

Fig. 3. Wear of work rolls depending on their type in case of rolling, low carbon steel, different than high-silicon steel – campaign 75 coils

Rys. 3. Zużycie walców roboczych podczas walcowania blachy czarnej w zależności od rodzaju walca – kampania 75 kręgów

When rolling high-silicon steel, the length of the campaign, in other words, the amount of material rolled, impacts tool wear. The longer the campaign, the greater the wear of the work rolls of the finishing mill. In the early finishing stands, where HSS-type work rolls are used, no significant difference was observed in the amount of tool wear depending on the amount of high-silicon steel rolled (**Fig. 4**).

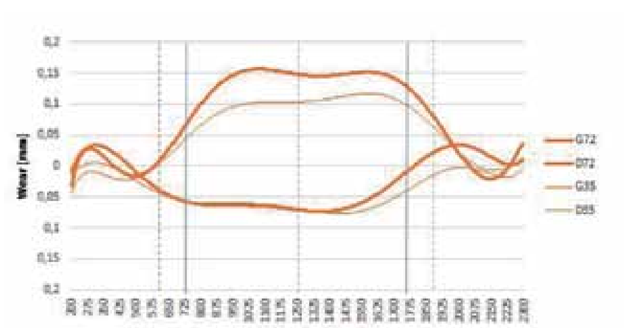

Fig. 4. High Silicon Steel – comparison of different quantities of rolled material – wear of rolls on stand No 3

Rys. 4. Stal wysokokrzemowa – zużycie walców w klatce walcowniczej nr 3 dla różnej ilości odwalcowanego materiału

The wear of the Hi-Cr work rolls in F4 increases with the amount of rolled material. The crown of work rolls also deteriorates with a higher amount of rolled material (**Fig. 5**).

The work rolls of F5 and F6 wear the fastest (**Fig. 6** and **Fig.7**). In order to ensure the highest strip quality and the best possible thickness cross profile, the set of work rolls of the finishing mills is purposely exchanged during the rolling campaign of the high-silicon steel. The work rolls of F5 are exchanged once after a certain amount of rolled material, while the work rolls of F6 are exchanged twice during the campaign. The amount of wear of the work rolls after rolling 35 and 50 coils of high-silicon steel is comparable for the work rolls of stand F5 **(Fig. 6).** Work rolls wear after rolling 25 coils of high-silicon steel, immediately after work rolls exchanges in **Fig. 6** and **Fig. 7** is indicated as G25W and D25W where W stands for work rolls exchanges. The wear value after work rolls exchanges is up to 0.15 mm in some places when rolling only high-silicon steel. Low carbon steel is not rolled after intermediate roll exchanges in this case, confirming the intensity of tool wear when rolling this type of steel.

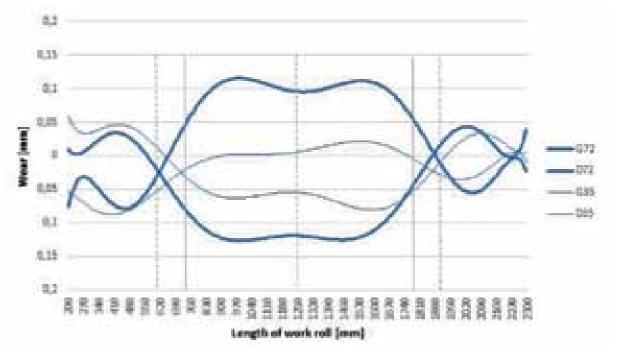

Fig. 5. High Silicon Steel – comparison of different quantities of rolled material – wear of work rolls from stand No 4

Rys. 5. Stal wysokokrzemowa – zużycie walców w klatce walcowniczej nr 4 dla różnej ilości odwalcowanego materiału

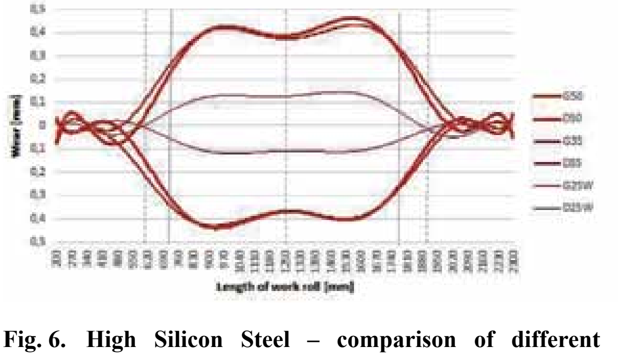

Fig. 6. High Silicon Steel – comparison of different quantities of rolled material – wear of work rolls from stand No 5, including wear of work rolls after stand's exchange

Rys. 6. Stal wysokokrzemowa – zużycie walców w klatce walcowniczej nr 5 dla różnej ilości odwalcowanego materiału, z uwzględnieniem zużycia po wymianie walców w trakcie kampanii

The wear of the work rolls of stand F6 increases significantly, even with a slight increase in the amount of rolled material when rolling high-silicon steel (**Fig.7**).

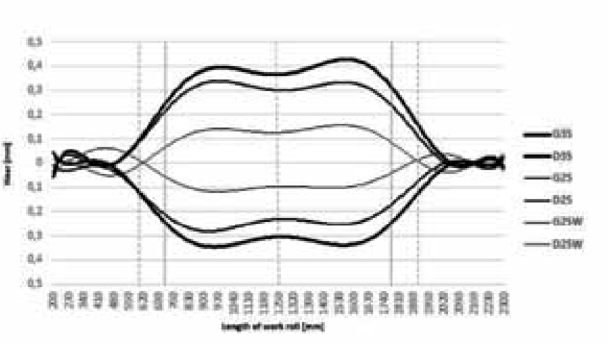

Fig. 7. High Silicon Steel – comparison of different quantities of rolled material – wear of work rolls from stand No 6, including wear of work rolls after stand's exchange

Rys. 7. Stal wysokokrzemowa – zużycie walców w klatce walcowniczej nr 6 dla różnej ilości odwalcowanego materiału, z uwzględnieniem zużycia po wymianie walców w trakcie kampanii

Comparing the wear of the work rolls of stand F6 while rolling different quantities of high-silicon steel with the wear of rolling 75 coils low carbon steel, we can observe that after rolling only 25 coils of high-silicon steel, the wear of the upper work roll in some places exceeds 0.3 mm, while after rolling 75 coils of low carbon steel it reaches a maximum of 0.22 mm (**Fig. 8**)

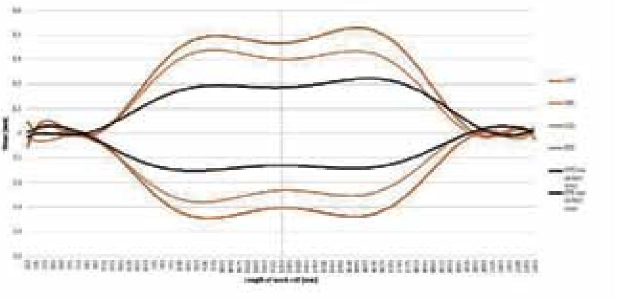

Fig. 8. Roll's wear from stand No 6 – comparison between rolling of low-carbon steel and high-silicon steel in case of different numbers of coils

Rys. 8. Zużycie walców roboczych F6 dla różnej ilości odwalcowanych kręgów blachy czarnej i stali wysokokrzemowej

CONCLUSIONS

- The hot rolling of high-silicon steel almost doubles the wear on the work rolls of the finishing mills. After rolling 75 coils of low carbon steel, the wear of the work rolls from stand F6 reaches up to 0.2 mm for the top roll and 0.15 mm for the bottom roll in some areas of the work roll's barrel (**Fig. 3**) while after rolling a campaign of high-silicon steel with a comparable total amount of rolled material, the wear on the top work roll F6 exceeds 0.4 mm in some areas and the wear on the bottom work roll reaches 0.35 mm. The high temperature of the rolled strip of high-silicon steel, the considerably reduced cooling, and the rolling campaign's length for the same width of material are the main factors influencing the wear of the work rolls.
- The wear of the work rolls depends on the type of material the work rolls are made of. The wear rate of HSS and Hi-Cr work rolls is lower in the rolling process of high-silicon steel than that of IC-type work rolls. The wear of HSS and Hi-Cr work rolls after the high-silicon steel campaign reached a maximum of 0.1 mm while, in the same rolling campaign, the wear of IC work rolls from stands F5 and F6 exceeded 0.4mm in places.
- The wear of the work rolls affects the quality of the rolled strip. Greater wear of the work rolls can cause quality defects in the strip by deforming its thickness cross profile. This disadvantage can be eliminated through the appropriate shifting of the work rolls and indirect exchange of the work rolls of finishing stands.

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