CARBIDE REINFORCEMENT FOR FINISHING MILL ROLLS AND THE EFFECT ON TEST RESULTS AND STRIP SURFACE*

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Abstract

Graphitic HSS roll grades such as ESW's brand VANIMO can be considered as the latest developments for the last finishing stands in hot strip mills. These roll grades are developed on the basis of the alloying concept of (Carbide Enhanced) Indefinite Chill work roll materials. During the development of VANIMO, the amounts and types of carbide forming elements were increased and adjusted into the direction of cast HSS roll grades. The microstructure of graphitic HSS roll grades therefore consists of tempered martensite, cementite and several different carbide types as well as a well-defined amount of free graphite. The main purpose of graphitic HSS roll grades is to combine the high surface quality of Indefinite Chill alloys as well as the high wear resistance of HSS roll grades. Several systematic steps were taken to increase the wear performance from Carbide-Enhanced Indefinite Chill grades to the more advanced VANIC grade and further on to the highest alloyed roll grade VANIMO. In every development step, the surface quality of the roll grades was carefully monitored. The decision to invest in new testing equipment at ESW's plant was driven by the wish to see microstructural effects of different alloys in a macroscopic dimension. Usually samples are taken from cast rolls and investigation is done in comparably small areas compared to the total surface of a roll. Rolling of strip is done with the entire barrel, so effects of alloy and microstructure can appear anywhere on the barrel surface. To ensure better understanding and deeper knowledge about influences of alloying trials we decided to install the last version of LRI (Lismar Roll Inspection). LRI includes the latest technology of Eddy Current with an enormous resolution. Depending on the formation of carbide precipitations, carbide network as well as matrix and free graphite, the EC test can detect smallest differences. The possibility to analyze the different results of EC and UT surface wave inspection will be discussed. A few examples of surface effects in the mill application will be discussed and improvement strategies explained.

Keywords: grafitic HSS, carbide enhancement, segregation, Lismar roll inspection.

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1 INTRODUCTION

Indefinite Chill cast iron (ICDP) alloys are used as shell materials of cast work rolls for highest demands on wear resistance and surface quality in hot rolling mills. The history of this alloy type reaches back until the 1930ies [1] and since that time it has been continuously modified and improved. The last big development step was the introduction of so-called carbide-enhanced types, where the microstructure was reinforced by Nb- and/or V-rich MC carbides. Nowadays the microstructure of Indefinite Chill alloys consists of tempered martensite, cementite (M_3C), graphite and MC carbides. [2-5]
To further improve the wear resistance of this alloy type, in the last years several approaches [5-9] were considered to develop graphite containing roll materials which consist of more wear resistant carbides than cementite. Within the rolling business this new alloy type was commonly called “graphitic HSS”.
Eisenwerk Sulzau-Werfen (ESW) as a leading roll manufacturer of high-performance work rolls for hot rolling mills looks back at a very successful history of Indefinite-Chill work rolls. The worldwide patent for the VIS grade [10] marked an important step in the development of more wear resistant Indefinite-Chill work roll grades. The history of graphitic HSS within ESW dates back until the year 2000 where the first prototype roll of VANIS was successfully produced and delivered. Today the product line for surface-critical work roll grades includes VIS, VANIC, VANIS and VANIMO and the most-suitable roll grade out of these can be selected for every application.

The developments of high-performing work roll grades were carried out in close cooperation with selected customers. Together more wear resistant roll grades were successfully introduced and tested. The rolls were closely followed by the HSM and systematically investigated by ESW. After the introduction of VANIC, VANIMO marked the next logical step. The chemical composition and the microstructure as well as the melting and casting procedure was continuously improved and a so a “fine-tuning” of this graphitic HSS grade was done.

2 MATERIAL AND METHODS

Metallurgy of graphitic HSS grades

ESW produces work rolls by means of the horizontal spincasting process, see Figure 1. The first step is the spincasting process itself (1) where the wear resistant shell material is cast at high centrifugal forces. The solidified shell material is mounted together with the spincasting mold to the bottom and top neck molds (2). As final step, the core material (usually nodular cast iron) is cast and the bonding zone between shell and core is formed (3).

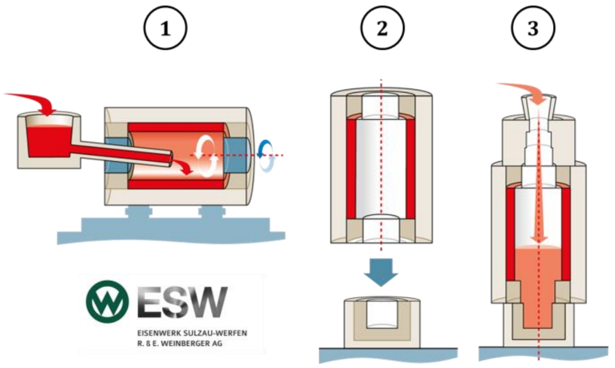

Figure 1: Production route of ESW’s horizontal spincasting process for work rolls [11]. 1: Spincasting of the shell material, 2: Mounting of the molds, 3: Casting of the core material

Graphitic HSS grades such as VANIMO are based on conventional ICDP grades but are strongly modified. This means, that both the chemical analysis and the microstructure originate from this very old alloy type. Table 1 shows the range of the chemical composition for conventional ICDP materials according to [2-3]. The C content is around 3 wt.-% and the fraction of Si can reach values between 0.7 and 1.3 wt.-%. Usually the Mn content is at low levels of about 0.5 wt.-%. Normally the fraction of Ni can reach levels of up to 3 times the amount of Cr in the alloy while Mo lies between 0.2 and 0.6 wt.-%.

	C [%]	Si [%]	Mn [%]	Ni [%]	Cr [%]	Mo [%]
Min	2.8	0.7	0.3	3.5	1.5	0.2
Max	3.5	1.3	0.8	5.0	2.0	0.6

Table 1: Typical chemical composition of conventional ICDP alloys in wt.-% according to [2-3]

The typical microstructure of conventional ICDP work roll shell materials consists of ledeburitic carbides $(Fe,Cr)_3C$ with an area fraction of 35-40 %, tempered martensite and (chainlike) graphite. In a conventional ICDP roll grade, the orientation of the graphite follows the solidification direction. [2]

The challenges for work rolls in the last finishing stands of hot strip mills can be summarized as follows [12]: The work rolls must have a low friction coefficient and a low sticking tendency, an excellent surface quality and a good resistance against cracks due to mechanical overload in the mill.

High-Speed Steel (HSS) work rolls are widely used in the early finishing stands of hot strip mills and these alloy types mark the benchmark for the wear performance of cast work rolls. [2] The chemical analysis of HSS work rolls is based on high amounts of carbide forming elements, see Table 2. Cr, Mo, W and V contents around 5 wt.-% or even more are typical for high-performing HSS work rolls.

	C [%]	Mn [%]	Ni [%]	Cr [%]	Mo [%]	W [%]	V [%]
Min	1.4	0.3	0.3	4.0	2.0	0.0	4.0
Max	2.2	0.8	1.2	8.0	6.0	5.0	7.5

Table 2: Typical chemical composition of HSS alloys in wt.-% according to [2]

Especially in the last years, the wish for both the roll user and the roll producer has been the development of roll grades which combine maximum wear performance with the good surface and operating condition of ICDP rolls. [5-9]

ESW's product portfolio for the last finishing stands reaches from Carbide-Enhanced ICDP (VIS) over a modified ICDP grade (VANIC) to graphitic HSS (VANIS and VANIMO), see Figure 2.

Figure 2: ESW's product portfolio for the last finishing stands of hot rolling mills.

The VANIC grade may mark an important intermediate step when introducing the very high alloyed graphitic HSS grades VANIS and VANIMO. Regarding the chemical composition of graphitic HSS in Table 3, the carbon equivalent (CE) can reach values higher than 4 wt.-%. The fractions of the carbide forming elements Cr, Mo, W, V and Nb are situated between the chemical compositions of conventional ICDP (Table 1) and HSS (Table 2).

	CE [%]	Mn [%]	Ni [%]	Cr [%]	Mo [%]	W [%]	V [%]	Nb [%]
Min	2.8	0.5	4.0	1.0	0.5	0.0	1.0	0.5
Max	4.2	1.5	6.0	3.0	4.0	3.0	4.0	2.0

Table 3: Possible ranges of the chemical composition for graphitic HSS grades such as VANIMO in wt.-%.

The microstructure of graphitic HSS roll grades consists, like in case of ICDP roll grades, of cementite and graphite embedded in tempered martensite. Additionally very hard carbides such as MC and M_2C/M_6C are present in the microstructure of graphitic HSS. A possible microstructure of VANIMO is shown in Figure 3.

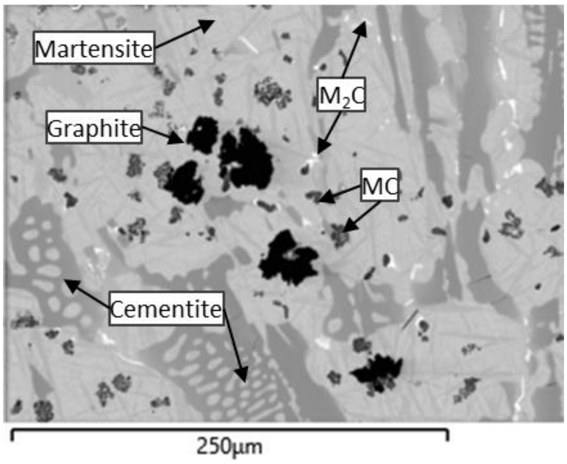

Figure 3: Microstructure of VANIMO with MC, M_2C and M_3C carbides as well as graphite embedded in tempered martensite

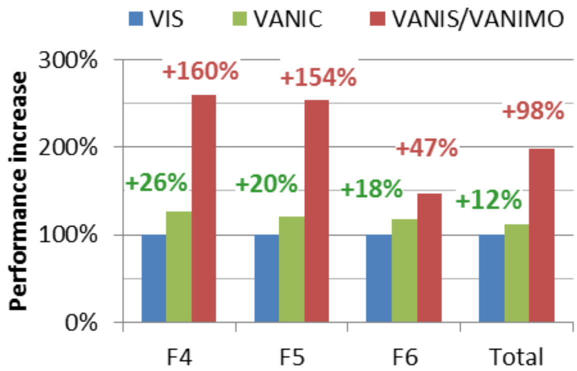

Figure 4: Wear performance of VIS, VANIC and graphitic HSS (VANIS/VANIMO) in the last 3 stands of a 7 stand mill

<u>Wear performance of VANIMO</u>

The wear of work rolls can be measured in rolled tons or rolled kilometers per mm shell material. Alternatively the average wear of all campaigns or the stock removal can be compared. In all cases it is important to exclude additional grind-offs which are related to incidents in the mill – otherwise the performance figure is misleading and the wrong work roll grade might be chosen for the application.
The performance of work rolls is compared in all of the mentioned ways. This means, that the additional stock removals due to mill incidents are clearly separated from the measured wear on the work rolls. Additionally not only the rolled tons but also the rolled kilometers per campaign are recorded and can be investigated.
Figure 4: Wear performance of VIS, VANIC and graphitic HSS (VANIS/VANIMO) in the last 3 stands of a 7 stand mill shows the comparison between VIS, VANIC and the graphitic HSS grades VANIS and VANIMO in regard to the rolled tons per mm shell material. In this case, the pure wear on the work roll is displayed (not the stock removal). Additionally the performance of the roll grades is compared for each stand separately.

It is obvious that the largest benefits were achieved in stand F4, where the performance of VANIC was +26 % in comparison to VIS and the graphitic HSS grades reached an increase of +160%. The higher wear resistance of VANIC and VANIMO can also be seen in stand F5 (VANIC +20 %, VANIMO + 154%), followed by stand F6 (VANIC +18 %, VANIMO +47 %).
In total, VANIC reaches +12 % in comparison to VIS while the graphitic HSS grades achieve +98 % in pure wear. These figures show that not only the work roll grade but also the rolling conditions influence the wear performance of the work roll. A close look at the work roll history helps to increase the performance of the rolls in the mill.
The superiority of the graphitic HSS grades to the carbide enhanced VIS and the modified work roll grade VANIC is evident and contributes to the reduction of the total cost of ownership (TCO) for the roll user.

<u>Improvement of the surface quality of VANIMO</u>

Graphitic work roll grades are used for surface critical applications in hot rolling mills. This means that the rolls serve in the last stands of hot strip mills and the surface of the barrel consequently is imprinted on the strip surface. Insufficient barrel surface qualities influence the quality of the strip surface which may cause quality issues for the hot rolling mill. Hereinafter some possible barrel surface quality problems are presented. The reasons for the defect type as well as the remedies are discussed.

Gravity segregation

The spincasting process is always related to high centrifugal forces. This means that due to the process so-called “gravity-segregation-effects” can occur within the liquid shell material as well as during solidification. If more wear resistant phases such as carbides agglomerate and segregate, the wear on the barrel surface develops irregularly and may look as shown in Figure 5
All phases follow Stoke’s law [13] and may segregate if their density is too different. This effect is even stronger if the process is overlaid by mechanical oscillations or vibrations.

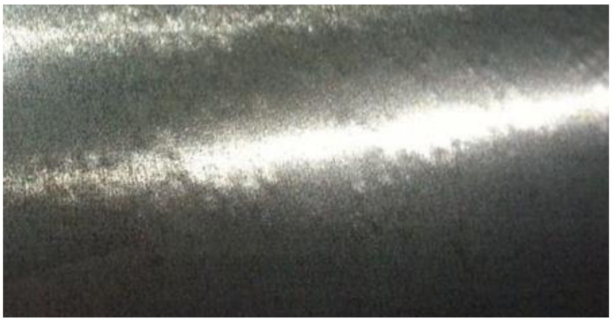

Figure 5: Possible appearance of segregated carbides on the barrel surface

An investigation of this surface shown in Figure 6 clearly shows agglomerations of small MC carbides, shown in white. MC carbides are the hardest carbide types [14-15] and therefore are highly wear resistant. If this carbide type is not distributed homogeneously in the matrix, the wear on the barrel surface develops irregularly.

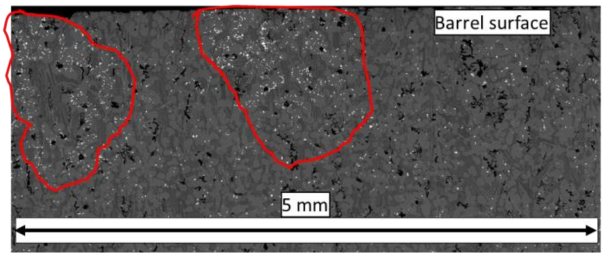

Figure 6: SEM-BSE investigations of segregated carbides in a graphitic work roll grade

The remedies for gravity segregations are:
Completely avoid extensive vibrations and oscillations during the spincasting process.
Adjust the chemical composition to ensure that the densities of the phases are similar.
Adjust the chemical composition to keep the solidification gap as narrow as possible.
Avoid nuclei (e.g. oxides or nitrides) which promote precipitation of carbides at high temperatures.

Insufficient dissolving of ferroalloys

When producing graphitic work roll materials, high amounts of alloying elements have to be added in form of ferroalloys. Some ferroalloys have very high solidus temperatures [16] and a proper dissolving in the melt may be difficult. In some cases, diffusion processes during melting of the ferroalloy may lead to additional challenges when alloying or correcting the chemical composition of the melt.
On the other hand, a full dissolution and homogeneous distribution of the ferroalloys in the melt is essential. Figure 7 shows a barrel surface with insufficiently dissolved ferroalloy particles which lead to imprints in the rolled material. During roll testing, these defects may be found by Eddy Current (EC) or UT surface wave testing. Also penetration testing (PT) or magnetic testing (MT) clearly reveal such defects where they appear as small cracks or porosities when they reach the barrel surface.

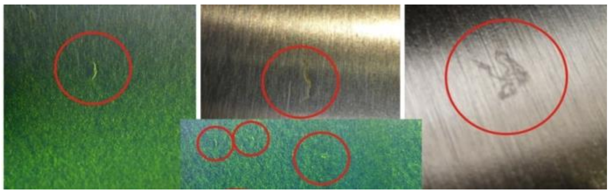

Figure 7: Typical appearance of insufficiently dissolved ferroalloys

If a metallographic sample is taken from such defect and etched with 5-% Nital, the microstructure looks as shown in Figure 8. In this image carbides appear white and the matrix as well as the graphite particles are black. The normal microstructure shows typical ledeburitic carbides with an area fraction of about 35 %. The insufficiently dissolved ferroalloy has a much higher carbide fraction and much finer structure.

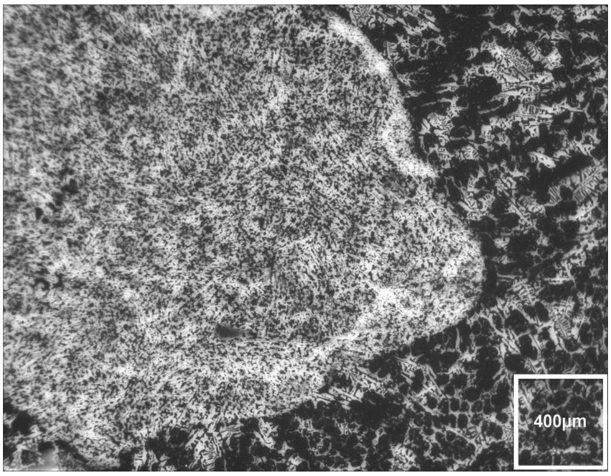

Figure 8: Light-optical image of an insufficiently dissolved ferroalloy

The depth profile of such defect is shown in Figure 9. The round graphite particles are shown in black, the matrix and cementite in grey. The insufficiently dissolved ferroalloy can be seen as a white structure. The depth of the particle is approximately 1 mm from the barrel surface. It can be clearly seen that the dissolving process was just in progress when the metal solidified. An EDX scan revealed that the particle contains high fraction of Nb which means that the dissolving process of FeNb was insufficient.

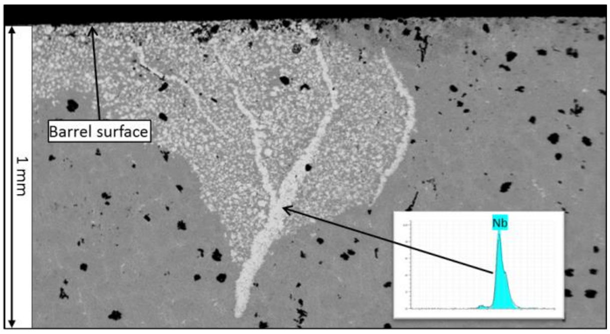

Figure 9: SEM-BSE image of the depth profile of insufficiently dissolved FeNb

The remedies for insufficiently dissolved ferroalloys are:
Reach an appropriate overheating temperature of the melt.
For diffusion processes, ensure enough time.
Lower the grain size of the ferroalloy (e.g. < 5 mm, < 2 mm).
Avoid gravity segregations in the furnace and the ladle.

Degenerated carbides

For high-performance work roll grades such as VANIMO, not only the correct amount and types of carbides but also their morphology is essential for a smooth barrel surface. Figure 10 shows an example, where "degenerated" carbides – this means carbides with different than usual morphology – lead to some surface pattern on the work roll barrel. The pattern in Figure 10 somehow reminds of water spots but is metallurgically caused.

Figure 10: Possible appearance of "degenerated" carbides on the barrel surface

The detailed view on such "water spot line" in Figure 11 reveals its macroscopically clear line appearance. Performing a large area EDX mapping which is shown in Figure 12 we see that the amount of V is not homogeneously distributed but V is enriched in one line which is the same as the macroscopically visible one.

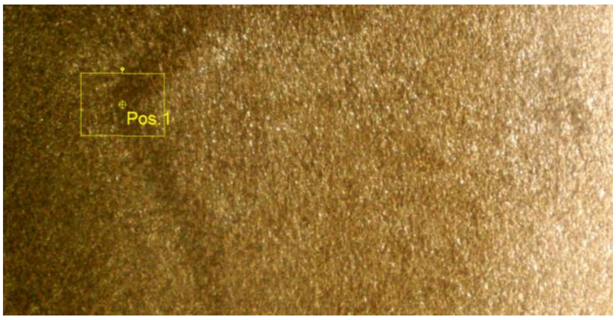

Figure 11: Detail of degenerated carbides in Figure 10

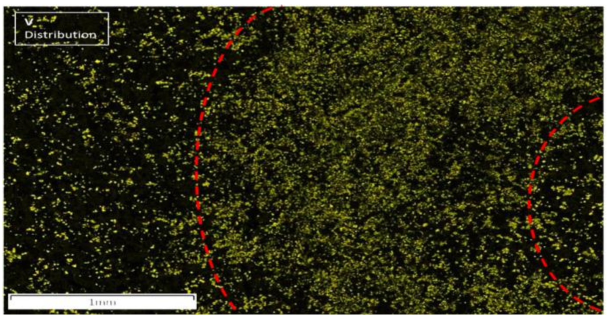

Figure 12: SEM large area mapping of V distribution

This is also valid for Nb (not shown here), which means, that MC carbides based on V and Nb are arranged in lines which cause the pattern on the work roll surface.

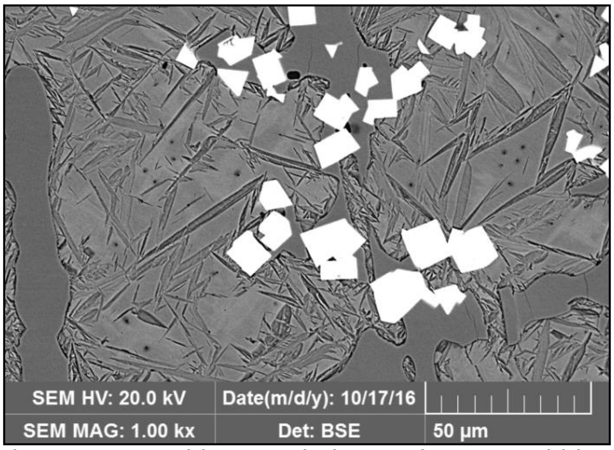

Figure 13: Cubic morphology of MC carbides (white) in a graphitic work roll grade

A close look on the morphology of the MC carbides shows clear deviations between two MC carbides types. The first type is shown in Figure 13, where the white MC carbides appear in a clear cubic structure.

The second type of MC carbides is shown in Figure 14. Here the white MC carbides have a more irregular shape. Else, they are much smaller than the ones in Figure 13. Additionally they tend to agglomerate and form lines which result in "water spot lines" on the barrel surface.

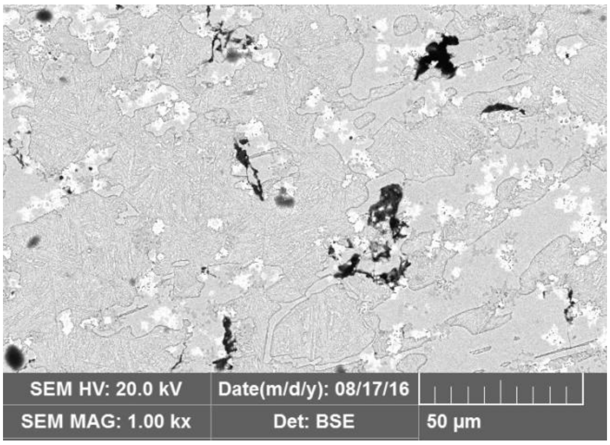

Figure 14: SEM-BSE image of degenerated MC carbides (white)

The search for the root cause of this defect requires intensive investigations including SEM/EDX investigations and thermodynamic calculations. It is known that the chemical composition of the carbides themselves influences or completely changes their morphology [17-20]. The remedies for this defect strongly depend on the root cause and are related to the chemical analysis of the melt and the degenerated carbides themselves. It is essential not only to look at obvious alloying elements such as V, Nb, Mo and Si [17] but among others also on small fractions of B [18], Ti [19] or N [20].

<u>"Cloud pattern"</u>

Up to now the defects on the barrel surface were clearly related to microstructural and therefore metallurgical aspects in roll manufacturing. A very critical phenomenon is the formation of a “cloud-pattern” on the surface of ICDP roll grades. Figure 15 shows the appearance of this defect on the barrel surface.

Figure 15: Barrel surface with “cloud-pattern”

It can be described as very small variations in the surface appearance of the work roll and can be very hard to identify. Anyhow in some mills and some applications the pattern is transferred to the strip where it is detected by the automatic surface inspection systems of the mills.
ESW’s experience with this defect is in full agreement with the investigations of [21], where a study about this effect for various ICDP roll grades from several reputable global roll producers was performed. This means that:
The phenomenon may appear intermittently.
No relation between specific parameters or periods was found.
It is not related to the mill stands and types (carbon/stainless steel, steckel/continuous mills).
Additionally it can be clearly stated, that there is no relation to specific ICDP roll grades but it is more likely that highly wear resistant grades (such as graphitic HSS) may form this pattern more easily. Else, it seems that some mills are more prone to form this defect.
From the position of a roll producer, the cloud-pattern is not related to variations in the surface profile, surface cracking, chemical segregations, bulk or microhardness. Additionally the microstructure does not correlate to this effect, including variations in the amount, distribution, size and composition of the graphite, cementite, martensite and retained austenite. [21]

Based on these results, it can be assumed that the rolling process with all parameters (temperatures, forces, cooling, grinding procedure,…) plays an important role in the formation of the cloud-pattern effect. Therefore it is essential to have close cooperation between the roll manufacturers and the rolling mills to determine the root causes of this phenomenon to finally prevent it.

Installation of LISMAR LRI

To get a better understanding of all those phenomena of surface patterns, ESW decided to make an investment in the future. So far ESW had investigated all the differently described cases on different samples taken from a roll. Therefore it was essential to have a roll with known defects where samples could be extracted. This was always in a late stage, mostly final grinding. ESW has been searching for a possibility to work pro-active. Means, to make changes in production and test the result directly in the company on large scale dimensions and not on very small metallographic sample. The studies of surface inspection systems of different suppliers revealed that ESW did not have an integrated testing system, which was able to react on such cases. Long time ago Lismar already had supplied the system Lismar Datames for roll testing, which was installed at ESW. The testing system consisted of several UT probes such as 2MHz straight beam, 4MHz TR and a surface wave probe.
With none of them a microstructural property could be detected. The new development of the EC probe from Lismar was the trigger to decide to make such an investment.
The key improvements of this new eddy current inspection technique are:

- Higher sensitivity for smaller cracks and detection of structure changes due to the EC reflection setup [22].
- Higher resolution and defect information due to use of small coils and digital signal processing.
- Faster scanning due to a wide array of coils within the probehead .
- Fully digitial and fast processing due to use of FPGA technology.

For ESW the improvement of a far better resolution and separation between crack and microstructural indications gave the breakthrough to invest. The improvements are a promise to detect described cases and have a quicker respons to support the investigations.

The installation of this new LRI system took place in August 2018. From that time on all roll scans are performed with eddy current and ultrasound inspection technology. This gives the oppertunity to analyze and compare or to find relations of those with all other filed parameters of the production process and test results.

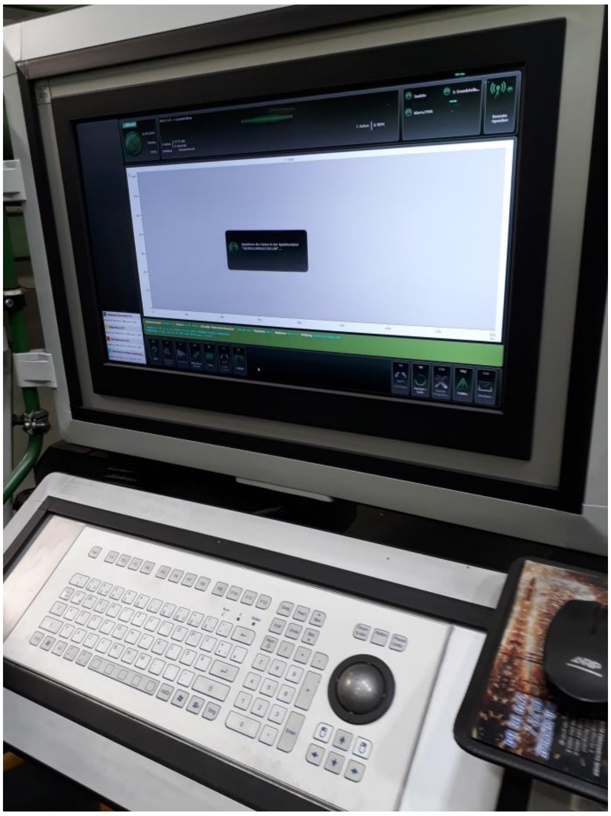

Figure 16: LRI Control Panel (Screen and PC)

The new LRI configuration is very compact. A controlpanel with screen and integrated PC as shown in Figure 16 is installed on the grinding machine. The second part is the so called iPPS (intelligent Probe Positioning System). This part controlls the probehead very accurate towards the roll surface to perform the automation. See Figure 17.

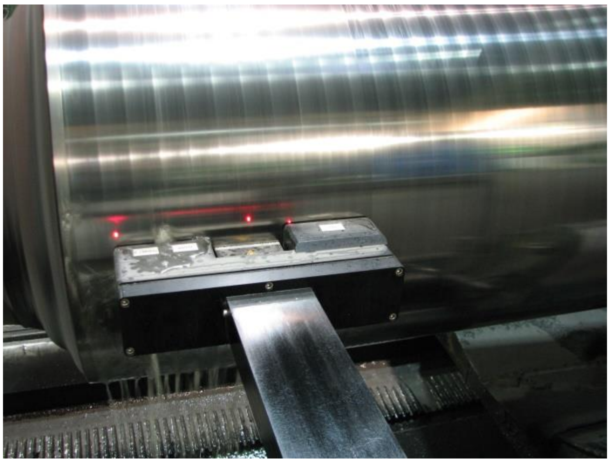

Figure 17: LRI intelligent Probe Positioning System

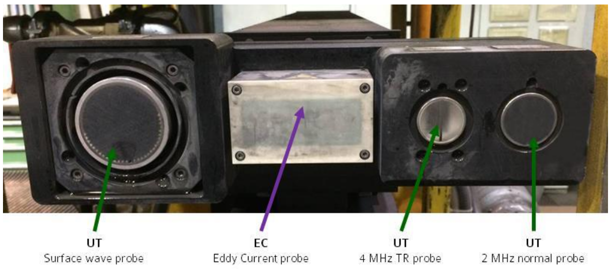

Figure 18: front of the probe head configuration

Figure 18 is showing the actual probe head configuration of this ESW automatic roll inspection system. There are the 3 described UT probes, same as in the former configuration and the new eddy current sensor in the center of the probe head.

After installation of the system it took some time to understand all the different test results and make the right interpretation. Quickly the first tests of different special cases have been performed and lead to remarkable results.

3 RESULTS AND DISCUSSION

3.1 Chrome steel roll examination

For this investigation we took a special alloy of chrome cast steel. To see if the alloy is uniform we ground the roll in 5mm steps down followed at each step by a scan on the LRI System. The following figures 19-23 show the different stages of the ground roll.

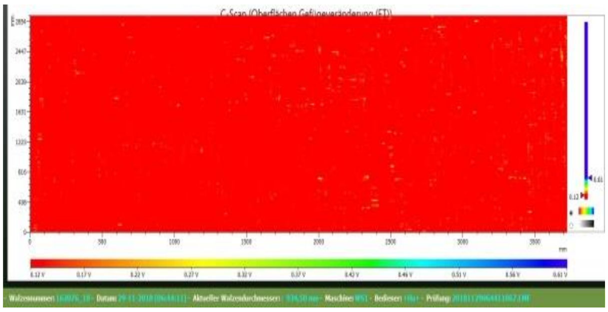

Figure 19: C-scan at Ø 935mm

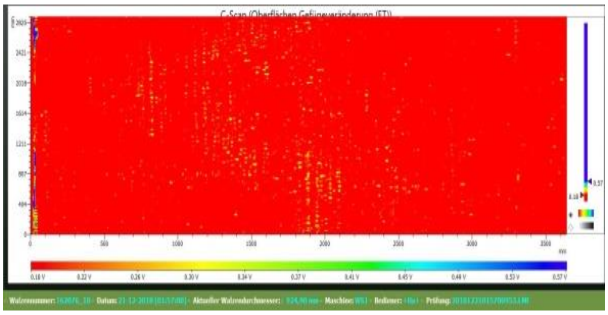

Figure 20: C-scan at Ø 925mm

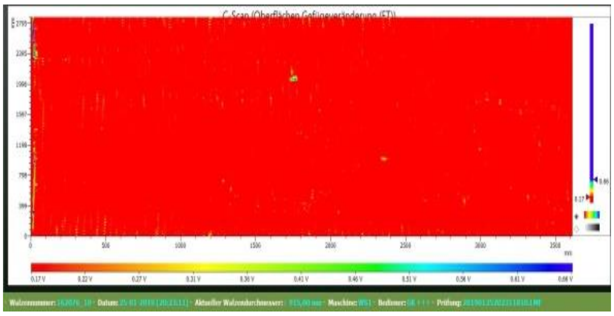

Figure 21: C-scan at Ø 915mm

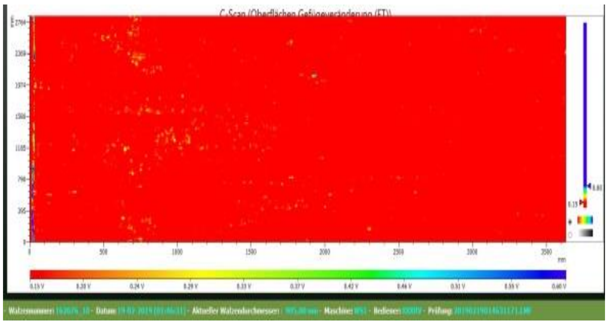

Figure 22: C-scan at Ø 905mm

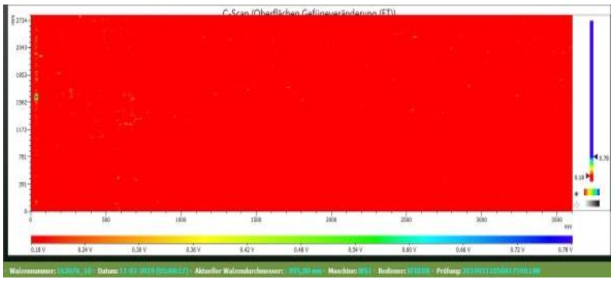

Figure 23: C-scan at Ø 895mm

In the different figures we can see, that some microstructural indications appear and disappear. The metallurgical background is a small variation in the carbide content of the ledeburitic network carbide.

3.2 HSS roll examination

A HSS roll was in service at a customer, when some indications on the test system appeared which could be highlighted by manual inspection.

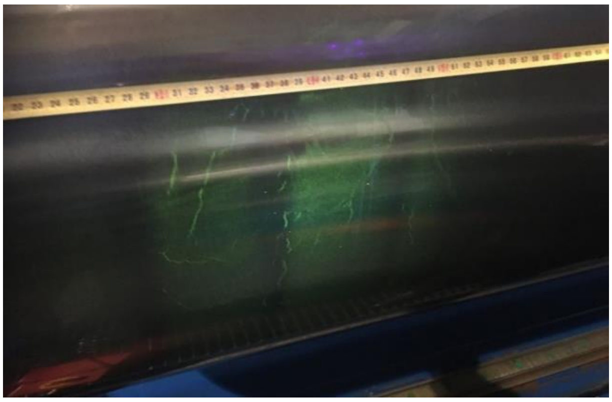

Figure 24: fluorescent magnetic particle test under UV light

Erro! Fonte de referência não encontrada. shows the detection of a surface pattern during service in the rolling mill.

The roll was one of the first rolls tested on the new LRI System at ESW. The post processing with changed parameters proved that some indications were already present during the tests at ESW. At that time the knowledge about different indications was not enough to decide not to deliver the roll to the customer. This investigation has lead to an adjustment of the evaluation threshold for the different channels.

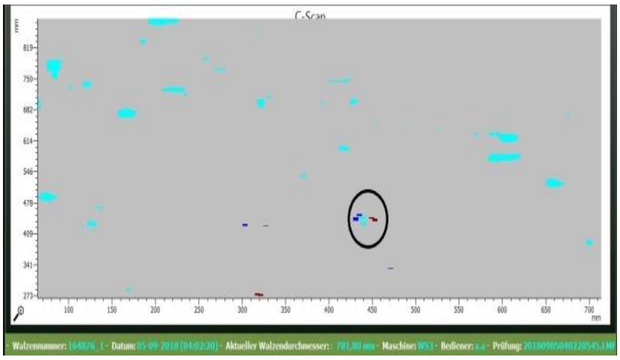

Figure 25: indication of dected area on the roll at customer side

Erro! Fonte de referência não encontrada. shows the detection in the circled area containing signals from the 2 directions of the surface wave probe and the EC microstructural indication.

3.3 Grafitic HSS roll examination

The EC microstructure of a HSS roll gave some indication as shown in Figure 26 and marked with the black circle.

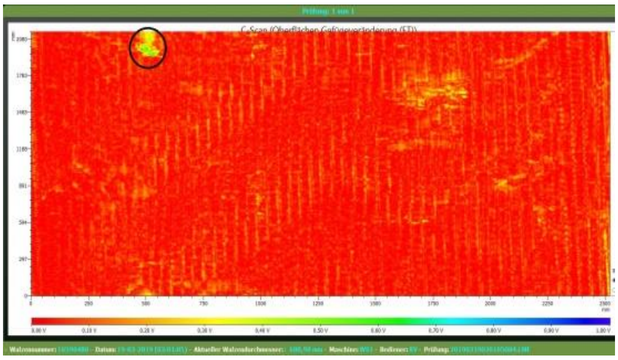

Figure 26: EC C-scan microstructure changes

Then metallographic investigation took place.

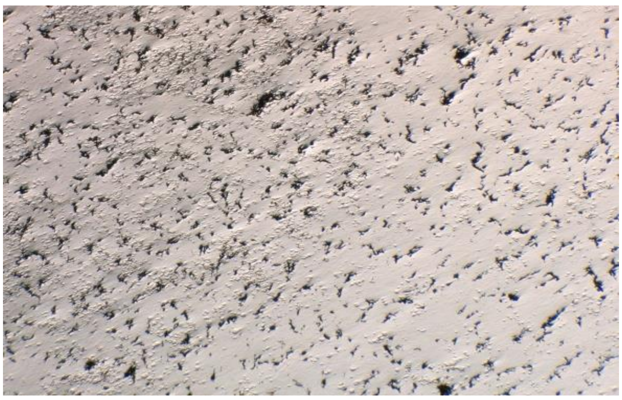

Figure 27: left top, MC carbide agglomeration

As can be seen in **Erro! Autoreferência de indicador não válida.**, the metallographic investigation brought up the high density of MC carbides. This gives a high signal in the EC microstructure channel. In total the MC precipitation was not uniform over the localized area in the barrel.

4 CONCLUSION

Graphitic HSS such as VANIMO are high-performing roll grades for the application in surface-critical stands in hot rolling mills. The wear performance of graphitic HSS grades VANIS/VANIMO is +98 % and therefore results in large benefits for the roll user.

The surface quality of ICDP as well as graphitic HSS grades is essential for a proper usability in the rolling mill. Possible surface defects were presented and the remedies were discussed. The new possibility to detect such surface discontinuities with EC test methods makes it possible to make tests inhouse and achive results in shorter time and less workload in the mill. Together with our customers we try to achieve a smooth barrel surface as shown in Figure 28.

Figure 28: Smooth VANIMO barrel surface without irregularities after rolling a campaign with ~4700 tons

REFERENCES

[1] F. Roll: Handbuch der Gießerei-Technik. Springer-Verlag. Berlin (1960). 321-328

[2] G. Lee: Rolls for the Metalworking Industries. Iron & Steel Society. Warrendale. USA (2002). 41-47

[3] H. Göbel: Neue Gußeisenwerkstoffe für Walzen. ihre Eigenschaften und Verwendungsmöglichkeiten. Stahl und Eisen 77 (1957). 143-157

[4] B. Feistritzer. K.H. Schröder. M. Windhager. K.H. Ziehenberger: Indefinite Chill: Upgrading an old HSM work roll grade. Proc. of the 41st MWSP Conf.. 21.-24. Oktober 1999. Baltimore. USA. 103-108

[5] A. Paar. M. Brandner. L. Elizondo. T. Trickl. C. Sommitsch. C. Béal: From ICDP to (graphitized) HSS: Sophisticated Work Roll Grades for Highest Demands in Rolling Mills for Flat Products. Proc. of the Rolling 2016 Conference. 6.-9. Juni 2016. Graz. Österreich

[6] S.V. Bravo. K. Yamamoto. H. Miyahara. K. Ogi: Control of Carbides and Graphite in Cast Irons Type Alloy's Microstructures for Hot Strip Mills. Materials Science Forum 561-565 (2007). 1023-1026

[7] T. Hattori. N. Oda. N. Meada: Latest development of cast rolls for hot strip mill finishing trains and other rolling mills. Proc. of the Rolls 5 Conf.. 22.-24. April 2015. Birmingham. Großbritannien

[8] N. Oda. P. Fleiner. T. Hattori: Latest Developments of a New Technology HSS Work Roll for Later Stands (F4-F7) in Hot Strip Mill Finishing Trains. Proc. of the AISTech 2013 Conf. and Expo.. 6.-9. Mai 2013. Pittsburgh. USA. 1977-1984

[9] C. Zybill. V. Goryany. M. Neumann. J. Buch. M. Römschmied: New Graphitised HSS Materials for Rolls in Finishing Stands. Stahl und Eisen 135 (2015). 10. 61-64

[10] Eisenwerk Sulzau-Werfen, R. &. E. Weinberger AG, 2000. Casting material for Indefinite rollers with a sleeve part and method for producing the same. Inventor: B. Feistritzer, K.H. Schröder, M. Windhager, K.H. Ziehenberger. WO 00/65118

[11] A. Paar, M. Brandner, M. Aigner, L. Elizondo, T. Trickl: Anzeigen bei der Ultraschallprüfung von Verbund-Indefinite-Walzen und deren Ursachen. Giesserei Rundschau 65 (2018), 5, 6-12

[12] S. Flament. G. Walmag. O. Lemaire. M. Sinnaeve: Development of a new grade for rear finishing stands based on modeling and evaluation of specific degradations. Proc. of the AISTech 2017 Conf. and Expo.. 8.-11. Mai 2017. Nashville. USA. 2667-2676

[13] T. Nylén: Niobium in Cast Iron. Proc. of the Int. Symp. Niobium 2001. 2.-5. Dezember 2001. Orlando. USA

[14] W. Theisen: Hartphasen. in Hartlegierungen und Hartverbundstoffe. H.H. Berns (Hrsg.). Springer-Verlag. Berlin (1998). 28

[15] N. Girschowitsch: Kristallisation und Eigenschaften von Gußeisen in Gußstücken. Verlag Maschinostroenie Moskau 1996. 562 ff

[16] ASM International: ASM Handbook Volume 3 - Alloy Phase Diagrams. (1992)

[17] E. Pavlina, C. van Tyne, J. Speer: Effects of combined silicon and molybdenum alloying on the size and evolution of microalloy precipitates in HSLA steels containing niobium and titanium. Materials Characterization 102 (2015), 35-46

[18] M. Cöl, F. Koc, H. Öktem, D. Kir: The role of boron content in high alloy white cast iron (Ni-Hard 4) on microstructure, mechanical properties and wear resistance. Wear 348-349 (2016), 158-165

[19] Q. Cen, Z. Jiang, H. Fu: Effect of Ti addition on the microstructure and properties of a High Speed Steel Roll. Materials Testing 55 (2013), 11-12, 871-876

[20] M. Ciesla, K. Ducki: Effect of increased nitrogen content on the structrue and properties of tool steels. Journal of Achievements in Materials and Manufacturing Engineering 29 (2008), 1, 15-22

[21] J. Jonck, J. Moema, J. Jooste, P. van Tonder: Investigation of the 'tiger skin' defect on indefinite chill rolls. The Journal of the Southern African Institute of Mininig and Metallurgy 116 (2016), 907-913.

[22] R. van Kollenburg, E. van den Elzen, S. Mul Practical Results of the Next Generation Eddy Current Technology for Roll Inspection – Aist 2016 Pittsburgh