Reconditioning of continuous casting machine rollers by laser cladding

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Abstract. The article presents the results of research of structures, compositions and tribological characteristics of coatings for continuous casting machine rollers. The coatings under research were obtained by methods of arc and laser cladding. The experiments were carried out on cylindrical samples of steel 20Cr13. A flux cored wire PP-Np-25Cr5VMoSi was taken as a material for cladding by the arc method. Sparingly alloyed iron-based powder Fe-Co-Cr-Mo was chosen as the material for laser cladding. The estimation of coating properties was carried out by the method of structural and phase analysis. Friction coefficients and wear rates for each cladding material were determined. The article offers an explanation of the differences in the properties of the coatings, which is based on the analysis of their formation conditions, as well as an assessment of the effectiveness of laser cladding in reconditioning of metallurgical equipment parts.

1. Introduction
Progress in steelmaking is closely connected with the introduction of continuous casting machines (CCMs). It is planned to increase the share of steel casting at CCM to 98-99% in 2020 [1].

Roller guides are important elements of a bow-type CCM.

CCM rollers are exposed to the following main factors: metal thermal fatigue caused by high-temperature thermal cycling; mechanical impact from the cast billet due to its weight and load resulting from ferrostatic pressure; high-temperature oxidation and corrosion.

As a rule, heat-resistant steel grades, such as 20Cr13, 25Cr1Mo1V, 40CrMnNiMo, 24CrMo1V are used for CCM rollers manufacturing in the domestic machine-building industry [2, 3].

Therefore, the work on increasing the resistance of the rollers is relevant.

One of the effective ways to increase the resistance of the rollers is to use reconditioning cladding. The most common is the method of submerged arc weld cladding.

Solid and flux cored wires (strips), such as Sv-20Cr13, PP-Np-25Cr5VMoSi, ASM 4603SA, Veltek H470S and others are used for reconditioning cladding of CCM rollers [4-8]. As of today, there is no single solution to the question of choosing a wire alloying system for reconditioning cladding [9]. As a rule, production conditions are unique for each particular enterprise and are determined by the
availability of this or that equipment in repair shops, operating conditions of recovered products, experience and qualification of production personnel.

For metallurgical enterprises the actual problem is not only reconditioning of geometrical parameters of worn out roller surfaces, but also creation of such operational features of a surface layer which will allow to increase essentially the repair interval of the specified parts while keeping economic expediency of their reconditioning.

In recent years, metallurgical enterprises have been researching the possibility of using new efficient technologies and materials for roller reconditioning, such as plasma-powder cladding, laser cladding, high-speed spraying, sprayfusing, the experience of which is described in the works [10-15].

In 2014 Precitec and Laser Line, together with Swansea University at the request of Tata Steel Strip Products UK investigated the potential of laser cladding for the reconditioning and strengthening of metallurgical and auxiliary equipment units. The conducted overall studies of the structure, physical, mechanical and service properties of coatings, as well as the results of industrial tests of CCM rollers, recovered by laser cladding technology with powder material developed by Swansea University, showed a significant increase in their resistance in comparison with the basic reconditioning technology – submerged arc weld cladding. The resistance of the submerged-arc weld cladded rollers amounted to 63,000 tons of steel, while for laser-cladded rollers it was 118,000...148,000 tons [16].

NUST MISIS together with the company LLC “VVST” conducted a set of researches aimed at studying the possibility of CCM rollers reconditioning (figure 1), made of steel 20Cr13 with laser cladding from iron-based sparingly alloyed powder material. At the present time, worn-out surfaces of these rollers are recovered by arc cladding with PP-Np-25Cr5VMoSi wire. The authors are tasked to increase the wear resistance of the roller cladded surfaces by two or more times while maintaining economic expediency.

2. Research techniques

The purpose of this work was to study the structure, composition and properties of layers obtained by laser and arc cladding technologies, as well as to evaluate the effectiveness of laser cladding.

The laboratory studies were carried out on samples (base plates) for cladding from steel 20Cr13 in the delivery state. Sample size was Ø60×60 mm.

By the method of arc cladding in 3 layers under the flux of AN-20S type the samples were cladded with the flux cored wire PP-Np-25Cr5VMoSi. Cladding was carried out on the machine USN 60-550/1400 SAW. Tempering of samples to relieve residual stresses was performed in EKPS-10 muffle furnace at 400 °C for 3 hours with subsequent cooling together with the furnace.

An iron-based sparingly alloyed powder (PEl1) with the Fe-Co-Cr-Mo alloying system was applied to samples by laser cladding. Subsequent thermal treatment was not performed.

The samples were cut on the LC-250 multifunctional cutting machine. The cutting was performed with a cutting wheel made of Al₂O₃ abrasive of Struers 50A30. Test sample size was 21×21×5 mm.
Polished specimens were prepared on the Struers Roto Pol-21 polishing machine in automatic mode. Struers abrasive papers with silicon carbide (SiC) grit size 120, 220, 500, 800, 1200, 4000 were used in series when polishing.

The samples were polished using a suspension of colloidal silicon oxide O-PS for finishing polishing with a grit size of 0.04 µm.

Hardness of the samples with cladded layers was measured according to GOST 9013-59 using TR 5006 durometer.

The microstructure of the cladded layers was studied with the Neophot-32 optical microscope and the Hitachi S-3400N scanning electron microscope equipped with the NORAN X-ray energy dispersive spectrometer.

X-ray phase analysis of the samples with cladded layers was conducted on the DRON-4 diffractometer using monochromatic Co-Kα radiation (wave length 1.79021 Å) and Cu-Kα radiation (wave length 1.54178 Å). The imaging was carried out in step scanning mode in the interval of angles 2Θ = 10°...130°; the imaging step was 0.1°, the exposure – 2...4 s.

The spectra processing was conducted with the help of qualitative PHAN and quantitative PHAN% analysis programs developed in NUST MISIS.

The tribological properties of the samples with cladded layers were evaluated in accordance with the international standards ASTM G 99-959 and DIN 50324 on a high-temperature friction machine High Temperature Tribometer CSM Instruments according to the pin-on-disk system. An Al₂O₃ ball with a diameter of 6 mm was used as a counterbody. The sample linear sliding velocity was chosen to be 10 cm/s, the load was 5 N. The dependence of the rubbing pair friction coefficient on the run length of the counterbody, equal to 500 m, was built on a computer using the InstrumX software.

The temperature of tribological tests was 500 °C, which corresponds to the temperature on the surface of JSC “OEMK” CCM No. 2 rollers, measured by SDS Hot Find-DXT thermal camera [2].

Wear track profile was investigated with Veeco Wyco NT 1100 optical profile meter.

Wear rate was calculated by the formula:

\[ W = \frac{s \cdot L}{(N \cdot l)} \]  

where W – wear rate, mm³:N⁻¹·m⁻¹; L – circular length, mm; s – groove wear section area, mm²; N – load, N; l – friction path, m.

3. Results and discussion

It was determined that the hardness of the cladded layers amounted to 43 HRC with laser cladding of PE11 material and 50 HRC – submerged arc weld cladding PP-Np-25Cr5VMoSi material.

![Figure 2. Cladded layer structure: micro-X-ray spectral analysis. a – laser cladding of PE11 material; b – submerged arc weld cladding PP-Np-25Cr5VMoSi.](image)

The structure of the cladded layer after laser cladding is shown in the figure 2a, the composition is presented in table 1.
Table 1. Elemental composition of the laser cladded PEl1 layer (figure 2a).

| Area | C-K | O-K | Cr-K | Fe-K | Co-K | Mo-L |
|------|-----|-----|------|------|------|------|
| 1    | 1.8 | 14.1| 13.1 | 67.9 | 2.2  | 0.9  |

Figure 2b shows the structure of the cladded PP-Np-25Cr5VMoSi layer, and table 2 shows its elemental composition.

Table 2. Elemental composition of the cladded PP-Np-25Cr5VMoSi layer (figure 2b)

| Area | O-K | Cr-K | Mn-K | Fe-K |
|------|-----|------|------|------|
| 1    | 27.8| 0.9  | 0.5  | 70.7 |

The phase composition of the cladded layers is shown in table 3. It was discovered that the cladded layers consist of two phases, the main phase in the samples α-Fe (martensite).

Table 3. Phase composition of the cladded layers

| Cladded material | Phase | Structure type | Pearson symbol | Mass fraction, % | Periods, Å |
|------------------|-------|----------------|----------------|------------------|-----------|
| PEl1             | α-Fe  | type A2        | cI2/1          | 82               | a = 2.880 |
|                  | γ-Fe  | type A1        | cF4/1          | 18               | a = 3.593 |
| PP-Np-25Cr5VMoSi | α-Fe  | type A2        | cI2            | 98               | a = 2.872 |
|                  | γ-Fe  | type A1        | cF4            | 2                | a = 3.587 |

The friction coefficient FC in the pair of a sample of the laser cladded material PEl1 – counterbody after 500 m of tests is 0.59 (figure 3a), in the pair of a sample 25Cr5VMoSi – counterbody – 0.5 (figure 3b), and for the laser cladded coating there are no abrupt changes in the friction coefficient, recorded for the sample obtained with the help of arc cladding. It is likely that a higher friction coefficient for a laser cladded coating is conditioned by the formation of a thinner film of chromium oxides on its surface at higher temperatures. At the same time, a thick film of iron oxides (wustite, magnetite, hematite) is most likely formed on the surface of a coating obtained with the help of an arc cladding, which is due to differences in the alloying system of the cladding materials. Thick oxide films can act as a solid lubricant and directly affect the value of the friction coefficient.

Figure 3. Dependence of the cladded layers friction coefficient on the counterbody run length: a – laser cladding of PEl1 material; b – arc cladding of 25Cr5VMoSi.

The profile of the sample wear track made of PEl1 and its three-dimensional image are shown in the figure 4. The wear rate of the sample is 58.9·10^{-6} mm^{3}·N^{-1}·m^{-1}.

The profile of the wear track of 25Cr5VMoSi sample and its three-dimensional image are shown in the figure 5. The wear rate of the sample with a cladded layer is 292.5·10^{-6} mm^{3}·N^{-1}·m^{-1}. 
As we can see, the sample with laser cladding of PEI1 material is characterized by a lower wear rate 4.95 times as compared to the sample with a cladded layer of 25Cr5VMoSi flux cored wire.

\[ a) \quad b) \]

**Figure 4.** Profile of the wear track of the sample with PEI1(a) cladded layer and its three-dimensional image (b).

\[ a) \quad b) \]

**Figure 5.** Profile of the wear track of 25Cr5VMoSi sample (a) and its three-dimensional image (b).

It is likely that the lower wear rate of the coatings is due to the peculiarities of laser cladding. Thus, precise dosage of laser radiation energy allows to ensure the degree of stirring of the cladding material with the main one not more than 3...7 % with the value of the thermal influence zone not more than 500 µm, as well as to ensure ultra-high cooling and solidification rates of the cladding metal, more than 103...104 ℃/s.

The solidification rate of the cladding metal determines its phase and structural composition, and therefore its resistance to wear, as a structurally sensitive property. In particular, higher solidification rates cause an increase in dispersibility of the resulting strengthening phases, which determine the wear resistance of coatings.

The local stress field, existing around the strengthening phase particles, complicates the dislocation movement at the plastic deformation preceding the destruction of the solid solution metal matrix, thus complicating its wearing [17]. Presumably, higher dispersion of hardening phases formed by laser cladding allows them to better perform barrier functions and to resist wearing.

Moreover, for the developed sparingly alloyed iron-based powder, the effect obtained at the work [18] for expensive nickel-based powders has been achieved. In particular, by alloying the powder with cobalt the durability of the obtained coatings to high-temperature wear has been increased and the mechanism of wear has been changed from the abrasive one observed for the submerged arc cladded sample to the adhesive one observed for the laser cladded sample (see the profile of the wear track of the sample in the figure 4 and 5, respectively).
According to the results of laboratory studies, it was decided to recondition the pilot batch of JSC "OEMK" CCM No. 2 third section rollers by laser cladding of PE11 material on the equipment and according to the technology developed by LLC "VVST".

By means of laser cladding with the use of fiber laser and six-axis industrial robot in the automated mode the coatings with thickness of ~3.5 mm were obtained (figure 6), the following heat treatment was not performed. Due to the low surface roughness of the coating, the machining allowance was 0.5 mm (at 3...6 mm submerged arc weld cladding), the surface roughness after the machining was Ra = 3.2 μm, no cracks or detachment was detected.

Figure 6. JSC "OEMK" CCM No. 2 third section rollers, reconditioned by laser cladding of PE11 material: a – after the cladding, b – after the machining.

Due to the reduced time for heat and mechanical treatment, the laser cladding technology allows, in comparison with the basic version of submerged cladding, to reduce the cost for CCM rollers repair by approximately 50% with the possibility of multiple repairs.

Currently, CCM rollers reconditioned by laser cladding of PE11 material are being prepared for industrial testing at JSC "Oskol Electrometallurgical Plant" CCM No. 2 third section.

4. Conclusion
It is established that the coating samples obtained by arc and laser cladding have different friction coefficients at elevated temperature (500 °C) and comparable loads (5 N) and sliding speeds (10 cm/s) – 0.5 and 0.59 respectively. This is probably due to differences in the alloying system of the cladding materials. Thicker iron oxide films formed on the coating surface cladded by an arc and 25Cr5VMoSi flux cored wire can act as a solid lubricant and directly affect the friction coefficient, while thinner chromium oxide films formed on the coating surface cladded by a laser from PE11 (Fe-Co-Cr-Mo) powder do not.

The sample with laser cladding of PE11 material is characterized by a lower wear rate of 4.95 times compared to the sample with 25Cr5VMoSi flux cored wire. Apparently, it is caused by ultra-high cooling and solidification rates of the laser cladding metal and increased dispersion of the resulting hardening phases that determine the wear resistance of the coatings.

Due to the alloying of the powder with cobalt the durability of the obtained coatings to high-temperature wear has been increased and the mechanism of wear has been changed from the abrasive one, observed for the submerged arc cladded sample, to the adhesive one for the laser cladded sample, as evidenced by the profile of the samples wear track.

By means of fiber laser and 6-axis industrial robot in automated mode the coatings with thickness of ~3.5 mm on the side were obtained without further heat treatment. Due to low surface roughness of the coating the machining allowance is 0.5 mm (at 3...6 mm submerged arc weld cladding), surface roughness after the machining is Ra = 3.2 μm. It was found that due to the reduced time for heat and mechanical treatment, the laser cladding technology allows, in comparison with the basic version of submerged cladding, to significantly reduce the cost of CCM rollers repair with the possibility of multiple repairs.
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