Innovative: International Multi-disciplinary Journal of Applied Technology
(ISSN 2995-486X) VOLUME 03 ISSUE 3, 2025

Modern Approaches to Clean Steel Production: Challenges, Methods, and Prospects

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1. Introduction

Modern metallurgical technologies are aimed at improving the purity of steels, as the content of non-metallic inclusions significantly affects the mechanical properties and operational reliability of the metal. In particular, titanium heterogeneity and secondary oxidation present serious challenges in the production of high-quality steels. These defects lead to deterioration in plasticity, fatigue strength, and corrosion resistance, reducing the service life of products.

The primary challenge in producing clean steels is controlling non-metallic inclusions that arise at various stages of the technological process. To minimize these defects, new methods are being developed to protect liquid metal from contact with oxygen, optimize deoxidation and vacuum processing, and improve refractory materials.

Research Objective – to analyze modern methods for reducing steel contamination with non-metallic inclusions, preventing titanium- and aluminum-containing defects, and developing recommendations for optimizing technologies to improve steel purity.[1]

2. Methods

The following methods were used in the study:

- **Literature analysis** – review of scientific publications and reports from metallurgical congresses on steel purity.
- **Experimental studies** – analysis of industrial data, including OEMK's experience in producing ShKh15 steel.
- **Metallographic analysis** – monitoring the size and composition of non-metallic inclusions in various steels.

- **Thermodynamic and mathematical modeling** – forecasting deoxidation and inclusion formation processes.

Particular attention was paid to analyzing factors affecting steel contamination, including metal-slag interaction, blowing characteristics, the use of inert gases, and the influence of ladle lining materials.[2]

3. Results

3.1. Effect of Titanium Content on Titanium Heterogeneity

High titanium content leads to the formation of titanium oxide, sulfide, and nitride inclusions, forming both edge and volumetric defects.[3] To minimize titanium oxide inclusions, it is necessary to:

- ✓ **Control titanium content** – maintain its level within an optimal range.
- ✓ **Use inert gases during casting** – to prevent contact between the metal and oxygen.
- ✓ **Apply special deoxidizers** – ensuring fine dispersion of inclusions.

Table 1 - Assessment of oxygen supply from the outside and the actual ranges of O, S and Mg content at all stages of the technological process.

<table>
<tr><th colspan="2" rowspan="2">Parameter and element in liquid steel</th><th rowspan="2">Release of melting into a steel ladle from a steelmaking unit (electric furnace or converter)</th><th rowspan="2">Extra furnace treatment of steel including calcium modification</th><th colspan="2">Casting of steel on UNRS</th></tr>
<tr><th>Section "intermediate ladle"</th><th>Section "crystallizer"</th></tr>
<tr><td colspan="2">Calculation in TMS of oxygen (O_2) from outside to metal, kg/t</td><td>1,000-5,500</td><td>0,100-4,500</td><td>0,005-0,100</td><td>0,001-0,080</td></tr>
<tr><td rowspan="5">Industrial data, mass. %</td><td>[O]раст.</td><td>0,03000-0,12000</td><td>0,00010-0,00700</td><td>0,00012-0,00045</td><td>0,00013-0,00050</td></tr>
<tr><td>[O] оксиды</td><td>0,00500-0,01000</td><td>0,00040-0,00300</td><td>0,00048-0,00300</td><td>0,00050-0,00350</td></tr>
<tr><td>[O] общий</td><td>< 0,13000</td><td>< 0,01000</td><td>0,00060-0,003450</td><td>0,00063-0,00400</td></tr>
<tr><td>[S]</td><td>0,0150-0,0400</td><td>0,0005-0,0070</td><td colspan="2">0,0008-0,0050</td></tr>
<tr><td>[Mg]</td><td>0,0010-0,0030</td><td>0,0005-0,0015</td><td colspan="2">0,0002-0,0010</td></tr>
</table>

3.2. Issues of Secondary Oxidation in High-Quality Steel Production

In the case of carbon structural steel with Al content (0.02–0.07%) and Si ≤ 0.03%, secondary oxidation leads to the formation of inclusions affecting the quality of cold-rolled sheets.[4] The main solutions include:

- ✓ **Optimization of slag-forming mixtures** – reducing aggressive metal interactions.
- ✓ **Protection of liquid metal in ladles and mold crystallizers** – preventing contact with air.[5]
- ✓ **Control of melt turbulence** – reducing the destruction of protective films on the metal surface.[6]

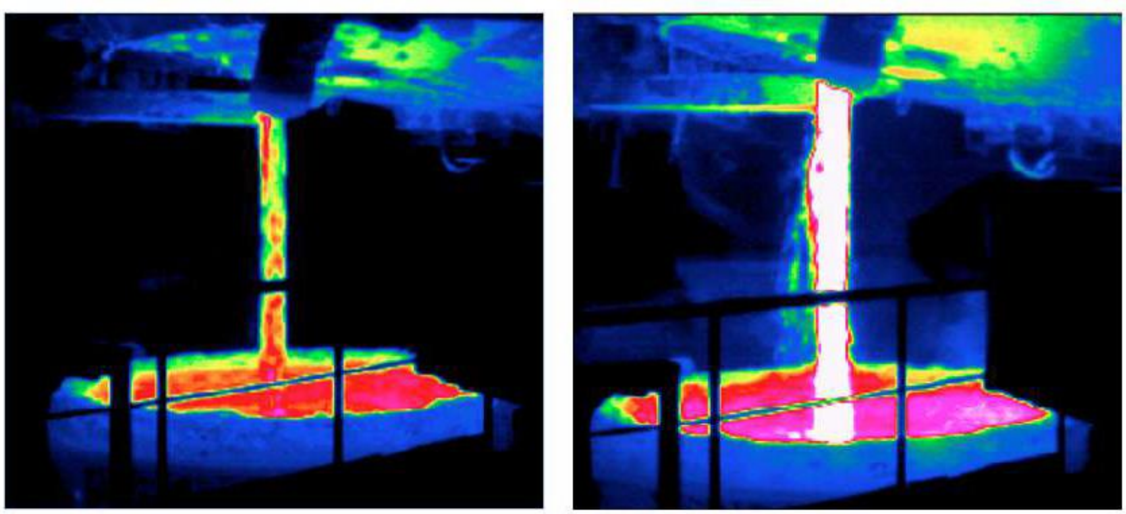
3.3. Impact of Casting Technology on Steel Quality

Analysis of continuous casting processes has shown:

- ✓ **Optimization of metal level in the mold** reduced the number of inclusions by 2 times.
- ✓ **Adjusting the metal outlet angle and immersion depth of the casting nozzle** decreased inclusion content by 2–3 times.
- ✓ **Application of special slag-forming mixtures (SFM)** reduced steel contamination.
- ✓ **Automated SFM feeding** lowered the edge point contamination (EPC) rating to 0.5.

Table 2. Argon purge mode of the steel ladle in the production of pure steels

Purge mode	**Technological operations**	**Total consumption of inert gas, l/(t^min)**		**Diameter of the purge spot, mm**
		minimum	**maximum**	
The beginning of purging	Blowing up the purge blocks before the aluminum wire is inserted	—	10,0	not controlled
Strong purging	Initial desulfurization	5,0	7,5	no more than 400 mm
Average purge	Heating, adding materials, and medium cooling of metal	2,5	5,0	no more than 300 mm
Normal purge	Heating, adding materials	1,2	2,5	no more than 150 mm
Soft purge	Inserting a modifying calcium wire and purging the melt without exposing the mirror	1,0	1,9	there is no purge spot
Cleaning purge	Final removal of non-metallic inclusions	0,5	1,2	



а б

Figure 1. – Comparison of melting outputs with a minimum amount of slag entering the steel ladle (a) and with an increased amount of slag (b) using an infrared camera

4. Discussion

4.1. Key Directions for Improving Clean Steel Production Technologies

Based on the analysis of recent studies, 12 key directions have been formulated:

1. Control of non-metallic inclusions – minimizing inclusions >40 µm.
2. Optimization of refractory materials – using stable materials (MgO, Al_2O_3) .
3. Improvement of deoxidation – reducing oxygen blowing intensity.[7]
4. Application of thermodynamic models – precise prediction of deoxidation.
5. Prevention of steelmaking slag contamination in casting ladles.
6. Minimization of secondary oxidation – controlling lining, casting, and stream protection. [8]
7. Casting under inert gas protection.
8. Steel vacuum processing – reducing sulfur and gas content.[9]
9. Optimization of the tundish – improving refining processes .
10. Control of ladle lining – preventing contamination.[10]
11. Personnel training – education and motivation.
12. Mathematical modeling of steelmaking processes.[11]

4.2. Common Errors in Clean Steel Production Technology

Twelve common problems have been identified :

1. Lack of comprehensive process analysis.[12]
2. Errors in deoxidation and steel modification.[13]
3. Insufficient control of inclusions and materials.[14]
4. Improper selection of refractory materials and SFM.
5. Inadequate protection of metal during casting.
6. Suboptimal design of casting equipment.
7. Low level of automated parameter control.
8. Ignoring mathematical models in process management.[15]

5. Conclusion

Optimizing clean steel production technologies requires a comprehensive approach, including:

- ✓ Development of non-metallic inclusion control methods.
- ✓ Optimization of casting and metal protection.
- ✓ Application of thermodynamic and metallurgical models.
- ✓ Automation and digital control of steelmaking processes.

Future research should focus on developing new methods for protecting metal from oxidation, improving inclusion analysis techniques, and implementing digital technologies in metallurgy. Modern approaches to clean steel production will enhance its quality and operational characteristics, which is particularly important for the aerospace, automotive, and energy industries.

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