Arch. Metall. Mater. **68** (2023), 3, 1025-1028

DOI: https://doi.org/10.24425/amm.2023.145470

T. WYLECIAŁ[1*], J. BORYCA[1], D. URBANIAK[2]

ANALYSIS OF THE EFFECT OF THE EXCESS AIR COMBUSTION RATIO ON THE LOSS OF STEEL AND SCALE ADHESION IN THE PROCESS OF HEATING THE STEEL CHARGE INCLUDING CHANGES IN TECHNOLOGY

Both the steel loss to scale and the scale adhesion are very important parameters of the heating process. High values of steel loss (large thickness of the scale layer) reduce the heat exchange intensity in the furnace chamber, which results in higher energy consumption. A low adhesion value adversely affects the operation of heating furnaces, while too high value causes the scale to roll into a steel product and deteriorate its purity and quality.

The paper presents the research methodology and the results of measurements of steel loss and scale adhesion. The effect of the excess air combustion ratio values on loss of steel and scale adhesion for constant furnace efficiency is discussed. This influence was described by mathematical dependencies. The tests were carried out for traditional technology and rational technology, enabling the reduction of steel losses to scale and energy consumption.

Keywords: heating of steel charge; loss of steel; scale adhesion; furnace exploitation

1. Introduction

Scale is an oxidation reaction product, usually formed on the surface of a metal or alloy. As a rule, solid oxidation products are formed as a result of oxidation of metals over a wide temperature range. According to the authors [1,2], we can talk about scale if the layer of the oxidation product formed on the surface of the metal, already in the first seconds of formation, has a thickness of 100 nm.

The basic elements determining the construction and phase composition of scales include:

- metal type,
- composition and pressure of the oxidizing environment,
- the temperature and duration of the oxidation reaction,
- concentration of alloying components in the metallic phase [1,3].

The formation of a multiphase scale depends on whether a given metal can form several thermodynamically stable compounds with an oxidant at elevated temperatures, differing in the degree of metal oxidation. The higher the degree of oxidation of the metal, the higher is the decomposition pressure of its oxidant compound at the same temperature. The phase composition of the scale depends primarily on the reaction conditions.

The scale formed during the steel heating to the plastic processing temperature consists of three iron oxides. They occur in the scale in the form of three parallel layers in the order corresponding to the oxygen content [4-6].

External factors are related to the oxidizing environment – its composition, temperature, pressure, gas speed and other parameters.

The most important external factors affecting steel oxidation include:

- heating time,
- temperature of the furnace working space (surface temperature of heated steel),
- composition of the gas atmosphere.

The research results indicate that in the CO_2 atmosphere the oxidation intensity is similar to that in the air, and the oxidizing properties of H_2O and SO_2 are much stronger. In this way, it is possible to explain the phenomenon of oxidation in case of combustion of fuels with a ratio of excess air $\alpha < 1.0$, when there is no free oxygen in the furnace chamber atmosphere [3,7,8].

---

[1] CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, FACULTY OF PRODUCTION ENGINEERING AND MATERIALS TECHNOLOGY, DEPARTMENT OF PRODUCTION MANAGEMENT, 19 ARMII KRAJOWEJ AV., 42-201 CZESTOCHOWA, POLAND

[2] CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, FACULTY OF MECHANICAL ENGINEERING AND COMPUTER SCIENCE, DEPARTMENT OF THERMAL MACHINERY, 19 ARMII KRAJOWEJ AV., 42-201 CZESTOCHOWA, POLAND

* Corresponding author: tomasz.wylecial@pcz.pl

The atmosphere in furnaces fired with gaseous fuels consists of highly oxidizing components, such as O_2, H_2O, less oxidizing components, such as CO_2 and reducing components CO, H_2, CH_4. Inert gas N_2 is also a component of the atmosphere, and when there is a large shortage of air, solid particles in the form of soot carbon are found in the atmosphere. In the case of complete combustion of fuel ($\alpha > 1.0$), the resulting exhaust gas contains CO_2, N_2, O_2 and H_2O. As the α value increases, the concentration of O_2 and N_2 increases, while the concentration of CO_2, and H_2O decreases. Such a composition of flue gases is oxidizing, and the oxidizing properties of flue gases increase with the increase in the value of α (with the increase in the content of O_2 in the flue gases).

In case of air shortage, there are CO, H_2, often CH_4 and C_{soot} in the flue gas, as well as, in smaller amounts, CO_2 and H_2O. Assuming a sufficiently small value of α, we can obtain no-scale heating [3,7].

In practice, in industrial heating furnaces, heating without traces of scale is difficult to achieve. However, it is possible to reduce steel losses multiple times. The values of the CO/CO_2 and H_2/H_2O ratios are important for the amount of steel lost. The values of these ratios depend primarily on temperature [3,7,9].

The composition of the gas atmosphere during the combustion of fuel gases can be simply determined by the value of the excess air ratio. Therefore, when conducting oxidation tests in flue gases, the steel loss is expressed as a function of the value of this ratio.

The problem of too high scale adhesion occurs in the processes of hot rolling of steel products [10,11] and hot stamping of car body parts [12].

2. Stand construction and measurement methodology

The test stand, the basic element of which is an electric tube furnace with a combustion chamber, was described in the paper [13].

The tests were carried out for "hot" samples using the mass method. The measurements were made by determining the scale adhesion measure as the ratio of the scale mass remaining after compaction (m_2-m_3) to the total weight of the scale (m_1-m_3). The masses m_0, m_2 and m_3 are determined by weighing the samples using an electronic balance WPS-360/C. The accuracy of the mass measurement is ±0.001 g. The dimensions of the samples were measured with a micrometre with an accuracy of ±0.002 mm. The methodology of measurements and calculations is described in detail in the papers [3,14,15].

The aim of the research was to determine steel loss and adhesion for various technologies ensuring constant furnace efficiency. The paper analyses the impact of the value of the excess air combustion ratio on steel loss and scale adhesion for traditional technology $T(a)$ and energy-efficient technology $T(b)$ with constant furnace capacity $w = 80$ t/h.

3. Results of measurements and calculations

The samples were heated in the flue gas atmosphere, for the value of the excess air combustion ratio $\alpha = 0.7 \div 1.3$ to the charge surface temperature $t = 1250$°C, according to the developed heating curves for the technologies $T(a)$ and $T(b)$ (Fig. 1).

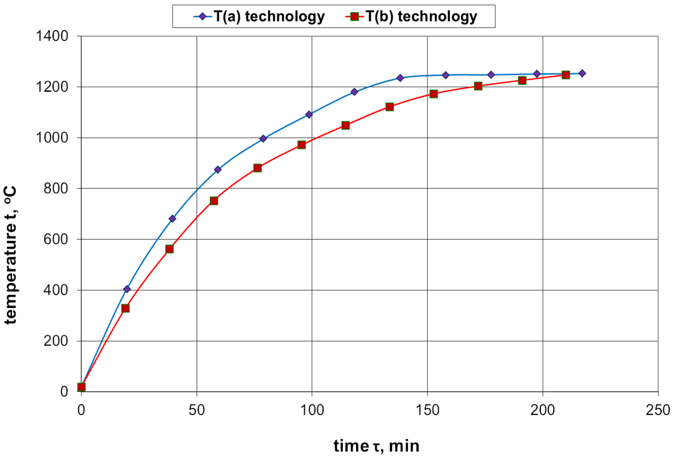

Fig. 1. Heating curves for technology $T(a)$ and $T(b)$ at capacity $w = 80$ t/h

Measurements and calculations of the sample masses and steel losses due to scale were carried out in subsequent stages of research. The results are summarized in TABLE 1 and TABLE 2.

The loss of steel and scale adhesion calculation results are presented in Fig. 2 and Fig. 3. Fig. 4 also shows the relationship of adhesion to steel loss.

TABLE 1

Results of measurements and calculations of geometric dimensions of samples

Value of excess air α, -	**Size of sample side a, mm**	**Sample height h, mm**	**Sample surface A, m^2**
Technology $T(a)$			
0.7	29.80	49.50	0.007676
0.8	29.85	49.65	0.007710
0.9	28.15	49.25	0.007130
1.0	30.25	50.65	0.007959
1.1	29.45	50.20	0.007648
1.2	28.50	50.15	0.007342
1.3	29.65	48.95	0.007564
Technology $T(b)$			
0.7	29.95	49.75	0.007754
0.8	29.55	50.15	0.007674
0.9	28.75	49.85	0.007386
1.0	29.85	49.65	0.007710
1.1	29.65	50.05	0.007694
1.2	28.75	50.05	0.007409
1.3	29.75	49.15	0.007619

TABLE 2

Results of measurements and calculations of sample masses at individual stages of testing

Value of excess air α, -	Initial mass of sample m_0, g	Sample weight after knocking off m_2, g	Sample weight after cleaning m_3, g	Sample weight after heating m_1, g
Technology $T(a)$				
0.7	312.763	309.330	297.089	333.944
0.8	311.354	304.512	293.598	335.349
0.9	313.543	302.536	289.523	346.002
1.0	312.585	296.145	281.452	354.657
1.1	313.174	291.582	278.238	360.385
1.2	314.434	287.487	275.574	366.948
1.3	313.987	281.892	270.063	373.344
Technology $T(b)$				
0.7	311.758	307.276	297.387	331.178
0.8	314.143	306.431	298.541	335.227
0.9	312.995	301.716	292.347	340.898
1.0	312.135	296.919	287.112	345.950
1.1	314.043	291.023	282.113	357.192
1.2	314.862	286.302	278.021	364.647
1.3	313.882	279.131	271.229	371.521

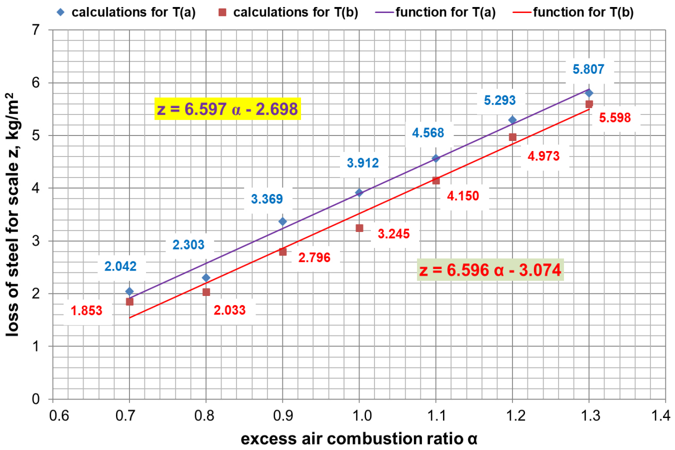

Fig. 2. Impact of excess combustion air ratio on steel loss

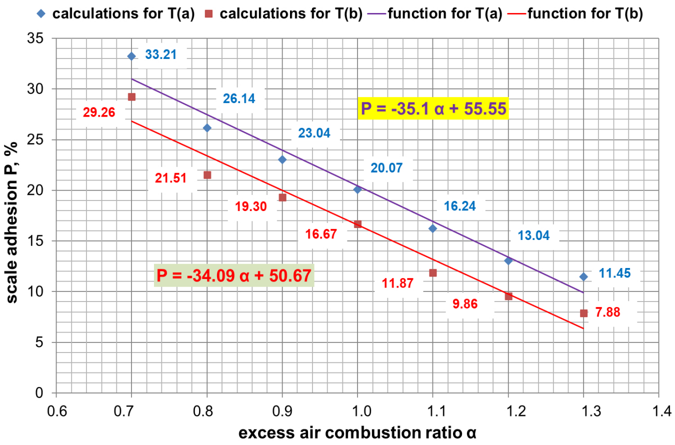

Fig. 3. Impact of the value of the excess combustion air ratio on the scale adhesion

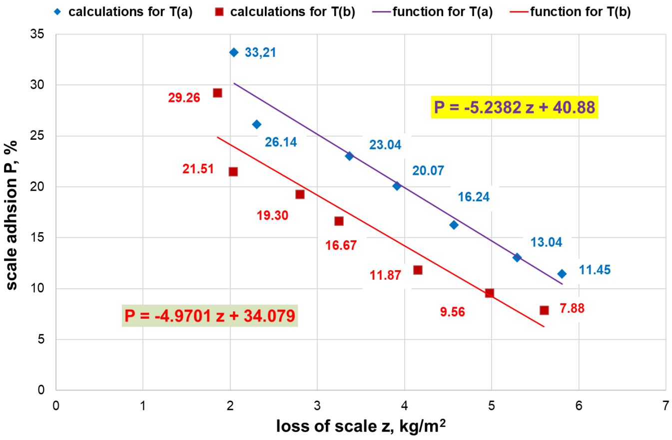

Fig. 4. Dependence of scale adhesion on steel loss

4. Conclusions

On the basis of the conducted research, the following conclusions can be made:

- The use of energy-efficient heating technology for a specific performance allows reducing both the loss of steel and the adhesion of scale to the steel substrate.
- The loss of steel per scale increases with the increase in the value of the excess combustion air ratio for both heating technologies used.
- The scale adhesion to the steel substrate decreases with increasing value of the excess combustion air ratio for both heating technologies applied.
- The influence of the value of the excess combustion air ratio on both steel loss and scale adhesion, for traditional and energy-efficient technology, can be described mathematically using simple linear relationships.
- There is a correlation between steel loss and scale adhesion. This correlation can also be described by a linear relationship for both technologies used.
- The increase in steel loss, for a given heating technology, is associated with a decrease in the scale‘s adhesion to the steel substrate.

REFERENCES

[1] S. Mrowec, Kinetyka i mechanizm utleniania metali, ”Śląsk”, Katowice 1982.

[2] A.T. Fromhold, Theory of Metal Oxidation, North-Holland, Amsterdam 1976.

[3] J. Boryca, Ph.D. Thesis Przyczepność warstwy zgorzeliny powstałej w procesie nagrzewania wsadu stalowego, Politechnika Częstochowska, Częstochowa 2005.

[4] H. Bala, Korozja materiałów – teoria i praktyka, Prace dydaktyczne Wydziału Inżynierii Procesowej, Materiałowej i Fizyki Stosowanej, Seria Inżynieria Materiałowa nr 5, Częstochowa 2002.

[5] M. Kieloch, Technologia i zasady nagrzewania wsadu, Skrypt Politechniki Częstochowskiej, Częstochowa 1995.

[6] K. Bae-Kyun, J.A. Szpunar, Scripta Materialia **44**, 2605-2610 (2001).

[7] M. Kieloch, Energooszczędne i małozgorzelinowe nagrzewanie wsadu stalowego, Prace naukowe Wydziału Inżynierii Procesowej, Materiałowej i Fizyki Stosowanej, Seria Metalurgia nr 29, Częstochowa 2002.

[8] N. Birks, G.H. Meier, Introduction to high temperature oxidation of metal, p. 74, Edward Arnold, Londyn 1983.

[9] M. Kieloch, Racjonalizacja nagrzewania wsadu, Ed. WIPMiFS Pol. Częstochowskiej, Seria Monografie nr 8, Częstochowa 2010.

[10] S. Chandra-ambhorn, J. Tungtrongpairoj, A. Jutilarptavorn, T. Nilsonthi, T. Somphakdee, Anti-Corrosion Methods and Materials **66**, 3, 294-299 (2019).

[11] Jae-Min Lee, Wooram Noh, Chanyang Kim, Seongsik Lim, Myoung-Gyu Lee, Mechanics of Advanced Materials and Structures, (2022).

[12] L. Levander, Improved Scale Adhesion of Uncoated Hot Stamped Steel, Proceedings of the 3rd International Conference on Advanced High Strength Steel and Press Hardening (ICHSU 2016) Edited By: Yisheng Zhang and Mingtu Ma, pp. 26-30 (2017).

[13] J. Boryca, C. Kolmasiak, T. Wyleciał, D. Urbaniak, J. Kizek, Research of the Impact of the Heating Rate on Adhesion of Scale Arising in the Process of Heating of the Steel Charge Before the Plastic Reworking, Chapter in the monograph „New Trends in Production Engineering" (ed.) Frączek Tadeusz, V. 2, Issue 2, SCIENDO, Warszawa 2019, p. 301-311.

[14] J. Boryca, M. Kieloch, Ł. Piechowicz, Archives of Metallurgy and Materials **51**, 3, 451- 457 (2006).

[15] J. Boryca, C. Kolmasiak, T. Wyleciał, D. Urbaniak, H. Otwinowski, Metalurgija **60**, 3-4, 368-370 (2021).