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Analysis of the Correlation Between Ferrous Scrap Quality and Metallic Yield in EAF Steelmaking

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Abstract

This article provides a statistical assessment of the impact of the grade structure and classes of steel scrap in the metal charge on the efficiency of the steel melting process in an electric arc furnace (EAF), measured by the liquid metal yield index. The research involved a two-stage procedure: first, an analytical simulation of changes in the mass of liquid steel depending on the configuration of metallic charge materials was performed, followed by statistical verification of actual production data obtained from heat cards under industrial conditions. The analysis was conducted using technological documentation on a population of 180 randomly selected heats from a domestic steel plant employing an electric arc furnace (EAF) in the steel melting process. The conclusions and mathematical relationships formulated based on the analyses are universally applicable. They can constitute a supporting tool for engineers in any electric steel plant, allowing the determination and optimization of scrap charge selection to simultaneously maximize technological yield and minimize operating costs.

Keywords: Steel, EAF, Ferrous scrap, Ferroalloys, Statistical analysis

1. Introduction and Core Relations

Electric steel works' role in the sustainable development of the steel industry is becoming increasingly important, offering solutions that combine economic profitability with environmental protection. Their significance will grow in the coming years, especially in the context of European and national strategies for reducing emissions and increasing recycling rates [1]. Despite dynamic technological development and increasing automation, modern steelmaking remains one of the most energy-intensive industrial sectors. It also accounts for approximately 8% of global carbon dioxide emissions. Due to growing environmental requirements and the need to reduce CO_2 emissions and the consumption of natural resources, electric steelmaking technologies are gaining importance [2]. Currently, low-emission metallurgy is expected; blast furnace processes and subsequent steel smelting in basic oxygen processes, which generate enormous amounts of CO_2 (1.6-2.3 tons of CO_2/ton of crude steel produced), are beginning to be reduced. Therefore, one of the key processes currently used in steel production is electric-arc steelmaking, which takes place primarily in electric arc furnaces (EAFs). Unlike traditional iron ore-based methods, electric furnaces use both post-production and post-depreciation steel scrap as input, making the process more environmentally friendly and energy efficient. Steel production in electric arc furnaces involves melting scrap using electricity generated by an electric arc formed between a graphite electrode and steel scrap. Precise control of the temperature and chemical composition of the alloy, as well as slag foaming [3], enables the production of very high-quality steel. Over the last

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decade, this research has focused on numerical and simulation modeling of individual furnace systems [4-6] and EAF process steps [7] the use of biochar as a foaming agent [8] the slag foaming process using plastic and rubber waste, carbonates, and nitrates and the slag foaming process with exogenous gas injection [9] optimization of the conventional slag foaming process [10-12] and the prediction of [C] content in molten steel obtained from scrap [12]. This process also allows for rapid adaptation of production to changing market needs. Shredders, devices that reduce scrap, including car wrecks, into a homogeneous steel fraction, play a special role in furnace feed preparation. Automatic separation of ferrous and non-ferrous metals from non-metallic materials allows for obtaining scrap with a high degree of purity, which directly translates into the quality and efficiency of smelting. The quality of ferrous scrap is a key factor influencing metal yield, energy efficiency, and steel purity in an electric arc furnace (EAF). Heavy structural scrap provides yields of over 94%, while light and oxidized scrap drastically reduces it to 46–61% due to excessive Fe → FeO oxidation [13 14]. Process optimization requires the use of strategies for proper scrap stacking in the basket, carbon injection to reduce FeO in the slag, and precise mass balance management [13-17].

2. Industrial Research Analysis

The analysis was conducted based on 180 randomly selected heats from a domestic steelwork that uses an electric furnace for steel production. Data was obtained from the technological documentation of selected heats produced in an electric arc furnace (EAF) with a capacity of 150 Mg. The main objective of the study was to determine the correlation between the charge composition (unalloyed charge scrap and ferroalloys) and the yield of liquid steel from the heat. This article presents an analysis of the impact of seven scrap classes: (W1, W2, W5, W8, W13, W18 – shredded scrap, WCIS – cast iron scrap) and WFS ferroalloys (introduced as deoxidizers).

To ensure research repeatability, metallic charge materials were classified according to the PN-85/H-15000 standard [18], which serves as a reference point for steel scrap classification in the Polish metallurgical industry. According to this standard, individual classes are precisely defined in terms of their geometry, mass, sorting origin, corrosion degree, and physical purity. These parameters directly influence the bulk density of the metal charge and the smelting process, and consequently, the final steel yield from the heat.

Due to the technologically required deoxidation process in the final phase of steel smelting in an electric arc furnace (EAF), appropriate ferroalloys are added to the liquid metal (usually during steel tapping). The iron contained in ferroalloys increases the effective mass of steel produced in this process. Therefore, the addition of ferroalloys to the charge should be considered when determining the liquid steel recovery rate from the heat as an "iron-bearing" component of ferroalloys. The steel recovery rate Y_{LS} and scrap share in the charge for individual scrap classes Z_{Wi} and ferroalloys Z_{FS} are calculated based on the following formulas [1, 19, 20]:

$$Y_{LS} = \frac{M_{LS}}{M_{W1}+M_{W2}+M_{W5}+M_{W8}+M_{W13}+M_{W18}+M_{WCIS}+\frac{1}{3}M_{WFS}} \cdot 100\% \quad (1)$$

$$Z_{Wi} = \frac{M_{Wi}}{M_{W1}+M_{W2}+M_{W5}+M_{W8}+M_{W13}+M_{W18}+M_{WCIS}+\frac{1}{3}M_{WFS}} \cdot 100\% \quad (2)$$

$$Z_{FS} = \frac{M_{FS}}{M_{W1}+M_{W2}+M_{W5}+M_{W8}+M_{W13}+M_{W18}+M_{WCIS}+\frac{1}{3}M_{WFS}} \cdot 100\% \quad (3)$$

where: Y_{LS} – yield of liquid steel from melting, %; M_{LS} – mass of liquid steel from melting, Mg; Z_{Wi} - The fraction of the i-th class scrap in the total mass of the metallic charge; ZFS – share of ferroalloys in the metallic charge, %; M_{Wi} – share of Wi class scrap in the metal charge, %; MCIS – mass of cast iron scrap, Mg; M_{FS} – ferroalloys mass (FeMn, FeSi), Mg; W1, W2, W5, W8, W13, W18, WCIS – class of scrap.

In the analyzed heats, individual scrap classes were not always present (e.g., class W1 was added to only 26 out of the 180 analyzed heats, presumably due to its price), which also applied to shredded scrap in classes W17 or W18. The classes presented in this paper were selected as representative examples. Frequently, in heats where class W1 scrap was absent, the proportion of class W2 or W5 scrap increased. During the process, the electric arc furnace was charged twice, and the mass of metallic charge materials in the charging basket was approximately 100 Mg in the first basket and approximately 67 Mg in the second. To determine the impact of the

metal input structure on the technological efficiency of the EAF process, regression and linear correlation analyses were conducted for the following scrap classes: W1, W2, W5, W8, W13, W18, WCIS, and WFS. **Class W1 (Medium Post-Production Scrap)**: Originates from metallurgical or mechanical working processes. Minimum wall thickness is **6 mm**, and maximum dimensions are typically 1000 x 500 x 500 mm. It is characterized by a low level of non-metallic impurities. **Class W2 (Light Post-Amortization Scrap)**: Consists of used components (stripes, wires, profiles, small structures) with a lower specific gravity. Minimum wall thickness is **4 mm**, and standard input dimensions are 1500 x 500 x 500 mm. Permissible impurity level is up to 2%. **Class W5 (Heavy Scrap, also known as Blue Coarse Scrap)**: Homogeneous, massive post-amortization scrap from industrial demolitions (steel structures, railway scrap, thick sheet metal, forge waste). Minimum wall thickness is **10 mm**, ensuring high bulk density and melting efficiency. **Class W8 (Short-Cut Scrap – from a shear baler)**: Fine piece scrap, often with a large proportion of cut pipe, profile, and sheet metal sections. The maximum dimensions of individual elements are 1000 x 500 x 500 mm. Prepared mechanically using shears. **Class W13 (Loose Steel Chips)**: Waste from machining carbon steel. Must be free of excessive oil, swarf, grinding dust, and other metal admixtures. Characterized by very low bulk density and a tendency to oxidize rapidly during the melting process. **Class W18 (Shredded/Comminuted Scrap)**: Raw material subjected to advanced mechanical fragmentation in shredders. The dimensions of at least 95% of the charge mass do not exceed 200 mm. This process allows for effective magnetic separation of impurities and non-ferrous metals, producing a product of high chemical purity. Characterized as very good input scrap. **Ferroalloys** are semi-finished metallurgical products consisting of iron alloys with one or more chemical elements (e.g. Mn, Cr, Si, Mo, V, W), in which the alloying element content is intentionally high. In metallurgy, they are not used as structural materials, but as **technological additives. Classes WCIS and WFS (Cast Iron Scrap):** Comprise high-carbon ferrous waste characterized by high bulk density, a compact structure, and low susceptibility to surface oxidation in the EAF atmosphere. The integration of these cast iron classes into the metallic charge effectively supplies primary carbon to the heat, thereby minimizing iron losses to the slag and significantly enhancing the overall metallic yield. The qualitative division and boundaries for individual ferrous and cast iron grades (WCIS, WFS) were adopted in accordance with the industrial standards derived from the Polish standard PN-85/H-15000 and aligned with the guidelines of the European Steel Scrap Specification [18].

Data from the production process was examined, where W1-grade scrap was present in 26 heats (number of samples n = 26), each containing heavy post-production scrap. The mathematical model describing the relationship between liquid steel yield (Y_{LS}, %) and the percentage share of the examined scrap grade (Z_{W1}, %) is: $Y_{LS} = 0.9126x + 82.299$. The positive slope of the regression coefficient (a = 0.9126) indicates that increasing the share of W1-grade scrap in the inserted basket directly translates into a linear increase in the mass of liquid metal – each additional percentage of this grade increases yield by approximately 0.91%. The coefficient of determination is ($R^2 = 0.5277$), which means that the variability in the W1-grade scrap share explains almost 53% of the variance in steel yield. In turn, the calculated Pearson linear correlation coefficient of r ~ 0.73 confirms that as many as 73% of the analysed heats from the research sample strictly meet the assumed linear relationship (Fig. 1). This demonstrates the high metallurgical stability of class W1 scrap and its low oxidation state, which allows for repeatable prediction of arc furnace operation and good steel yield from heats under industrial conditions. The remaining deviations result from variable operational parameters of the EAF process, such as the dynamics of oxygen purging and the heat holding time under current.

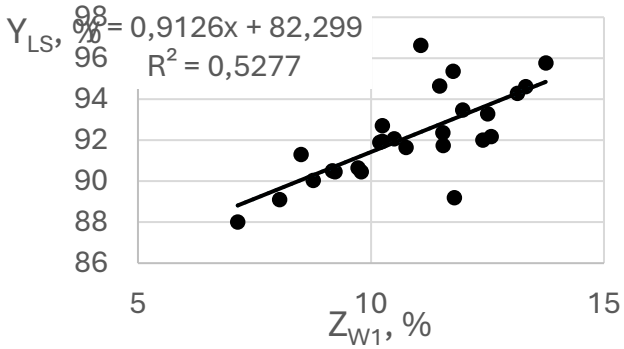


Fig. 1. The impact of the share of W1 scrap on the liquid steel output

The next part of the research analyzes the impact of the share of W2 scrap (Z_{W2}, %) on the yield of liquid steel (Y_{LS}, %). In this case, the experimental basis was a much larger sample, encompassing 178 heats from the EAF. The regression and linear correlation analysis demonstrated dramatically different characteristics of this charge compared to the previously discussed scrap class. The trend line determined by the least squares method is characterized by a nearly horizontal, slightly negative course, indicating a lack of a clear linear correlation between the variables studied. The regression slope close to zero and the very low value of the coefficient of determination $R^2 = 0.0018$ indicate that the percentage of W2 scrap in the charged basket alone is not a factor determining the final steel yield from the heat. Variation in the Z_{W2} parameter explains only 0.18% of the total variance in the dependent variable Y_{LS}. The remaining 99.82% of the variability is due to other factors (e.g., measurement errors, process fluctuations, or the influence of other independent variables). The linear regression equation takes the form: $Y_{LS} = -0.0117x + 91.763$. The slope of line a = -0.0117 is close to zero. The distribution of experimental points in Figure 2 shows a very high scatter (from approximately 85% to 96% yield) across the entire analyzed feedstock range (14–49%). This situation is justified by the physicochemical specificity of class W2 scrap.

Consequently, the yield of liquid steel in this group of heats becomes highly random and depends mainly on other operational factors of the EAF furnace – such as the degree of slag oxidation, duration of technological operations – and not on the mass fraction of this class of scrap itself.

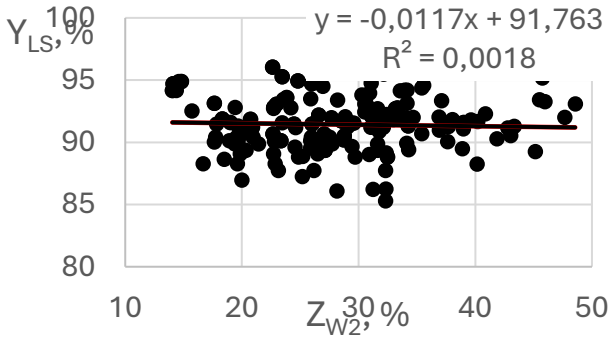


Fig. 2. The impact of the share of W2 scrap on the liquid steel output

The next stage of the research was to assess the impact of the share of W5-grade scrap (Z_{W5}, %) on the liquid steel yield index (Y_{LS}, %) under EAF operating conditions. In this case, the regression and linear correlation analysis covered a much broader research sample, encompassing 120 production heats containing W5-grade scrap. The determined regression function took the following mathematical form: $Y_{LS} = 0.1045x + 88.783$. The regression slope a = 0.1045 indicates a positive trend, but its dynamics are nearly nine times lower compared to the W1-grade. Each additional percentage of W5-grade scrap in the charge structure generates an increase in yield of only approximately 0.10%. The coefficient of determination of $R^2 = 0.1295$ and the related Pearson correlation coefficient r ~ 0.36 indicate a weak linear relationship. The share of W5 scrap determines only about 13% of the variance in liquid steel yield. This high dispersion of experimental points around the regression line (Figure 2) is a direct consequence of the physicochemical properties of W5 scrap. As a charge with a lower bulk density and a higher degree of surface development, it is much more susceptible to oxidation by the electric arc and the furnace atmosphere.

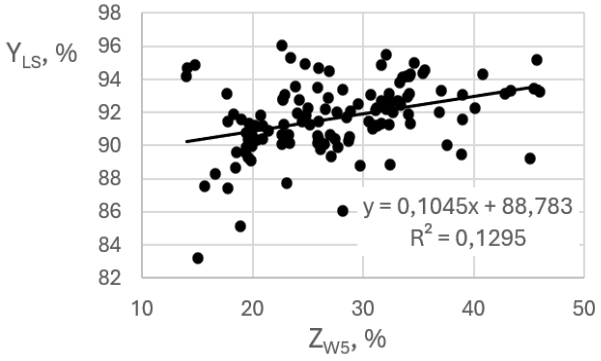


Fig. 3. The impact of the share of W5 scrap on the liquid steel output

This generates high iron losses to slag (FeO) and increases the share of the slag phase, making the yield prediction process highly sensitive to other melting operational parameters (e.g., oxygen blast intensity or slag foaming degree).The next stage of the research was the analysis of the effect that the W8 scrap share (Z_{W8} %) has on liquid steel yield (Y_{LS}, %). The experimental data set included a sample of 97 heats from an EAF electric arc furnace. The function determined by linear regression takes the following mathematical form: $Y_{LS} = 0.057x + 90.729$. The regression slope a = 0.057 is close to zero, indicating an extremely weak, even negligible, rate of yield increase with increasing the share of this charge class. The coefficient of determination of $R^2 = 0.0249$ confirms that the variation in the W8 scrap share explains only approximately 2.5% of the variance in metal yield. This indicates a lack of a statistically significant linear relationship between the parameters studied. Analysis of the distribution of experimental points in Figure 4 reveals a trimodal (cluster) structure specific to industrial practice. The data focuses on three fixed W8 scrap dosing ranges: 6–8%, 13–15%, and 19–22%, resulting from the use of unified feeder basket recipes at the steelworks. Within each of these clusters, a very high vertical dispersion of yield values is observed (for example, in the 13–15% range, yield ranges from 86% to nearly 96%). From a metallurgical perspective, this high process randomness demonstrates that the W8 grade exhibits characteristics of a technologically passive feedstock – its impact on melting efficiency is minimal, and the final liquid steel yield is almost entirely dominated by other EAF operating parameters, such as the bath oxidation state, energy profile, and the quality of the other grades fed into the basket.

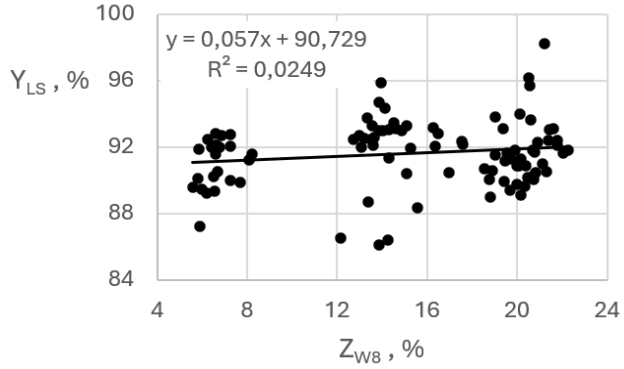


Fig. 4. The impact of the share of W8 scrap on the liquid steel output

Next, the analysis of the effect of the W13 scrap content (Z_{W13}, %) on the liquid steel yield (Y_{LS}, %) was conducted. The experimental basis in this case was a sample of 149 heats from the EAF. The determined linear regression function takes the mathematical form: $Y_{LS} = 0.0078x + 91.604$. The regression slope a = 0.0078 is close to zero, indicating an almost completely horizontal trend line. In turn, the coefficient of determination $R^2 = 0.0029$ (Pearson correlation coefficient r ~ 0.05) clearly demonstrates the lack of any significant linear relationship between the dosing ratio of this component and the final heat yield.

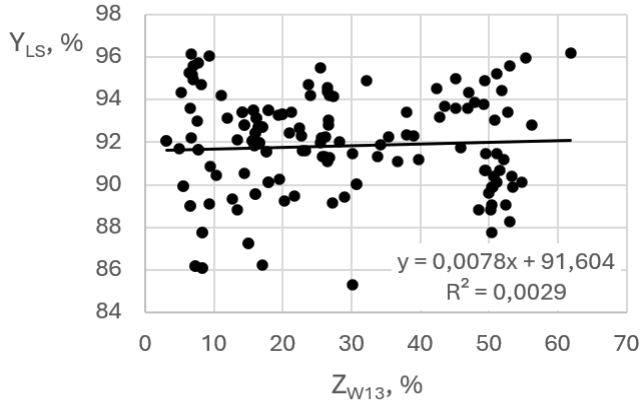


Fig. 5. The impact of the share of W13 scrap on the liquid steel output

The variation in the W13 scrap content explains only 0.29% of the variance in liquid steel yield. Analysis of the empirical point distribution in Figure 5 indicates a very wide range of use of this charge class in industrial practice – from marginal shares of approximately 3% to a dominance of the charged steel exceeding 60%. Despite this broad spectrum, steel recovery across the entire range exhibits a significant, random scatter (from approximately 85% to 96%). Also noteworthy is the specific behavior of the process at high shares of 48–54%, where a clear stratification of the data into two independent subgroups is visible: heats with high recovery (93–96%) and heats with reduced efficiency (88–91%). This phenomenon suggests that with high concentrations of W13 class scrap in the charged basket, the final metallurgical result becomes critically dependent on external factors, such as the chemical composition of the primary slag, the degree of bath decarburization, and the furnace's energy parameters.

In the next stage of the partial analysis, the effect of the share of W18-grade scrap (Z_{W18}, %) on the liquid steel recovery rate (Y_{LS}, %) was examined. This steel grade was present in 42 EAF heats. The linear regression function determined through estimation took the following mathematical form: YLS = 0.4867x + 88.714. The positive regression slope (a = 0.4867) confirms a strong, deterministic upward trend. Each percentage increase in the share of W18-grade scrap in the inserted basket structure generates a linear increase in liquid metal recovery by nearly 0.49%. The coefficient of determination of R^2 = 0.6097 indicates a high degree of model fit. This means that the percentage share of W18 scrap alone explains nearly 61% of the variance in steel recovery. The determined Pearson linear correlation coefficient of (r ~ 0.78) demonstrates a strong statistical relationship. Analysis of the empirical distribution of experimental points (Figure 6) indicates a relatively narrow range of use of this charge class in industrial practice (from approximately 3% to 11%). The small scatter of points around the trend line across the entire analyzed spectrum confirms the high metallurgical stability and qualitative repeatability of W18 grade scrap. Limited iron losses in the oxidation process allow for highly precise forecasting of steel yield under EAF operating conditions based on the share of this component.

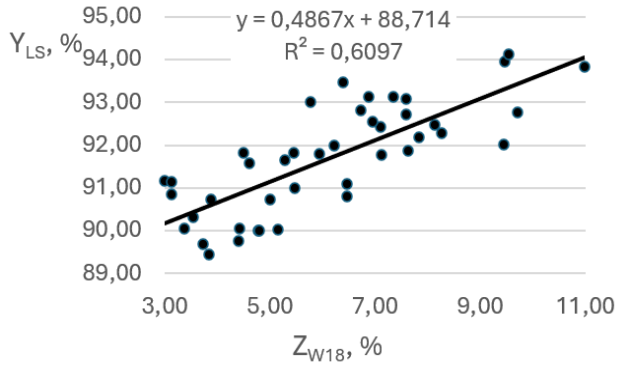


Fig. 6. The impact of the share of W18 scrap on the liquid steel output

The penultimate element of the charge structure analysis was to examine the effect of the share of WCIS-class cast iron scrap (Z_{WCIS}, %) on the liquid steel yield (Y_{LS}, %). This study was conducted on a representative sample of 157 industrial heats from an EAF. The mathematical linear regression model describing this relationship was determined as follows: Y_{LS} = 0.4168x + 89.115. The regression slope a = 0.4168 indicates a theoretical, significant increase in yield – each subsequent percentage increase in the share of cast iron scrap increases the expected yield by nearly 0.42%. However, the coefficient of determination at the level of R^2 = 0.0658 (which corresponds to a very weak Pearson correlation (r ~ 0.26) clearly proves that the mass fraction of the ZWCIS grade alone explains only about 6.6% of the variance of the liquid steel yield. Such a low degree of model fit and a high vertical scatter of experimental points (concentrated mainly in a narrow dosage range of 4–8%) are a direct consequence of the metallurgical specificity of melting cast iron in an electric arc furnace (Figure 7). The WCIS grade introduces a high load of carbon and silicon into the metal bath.

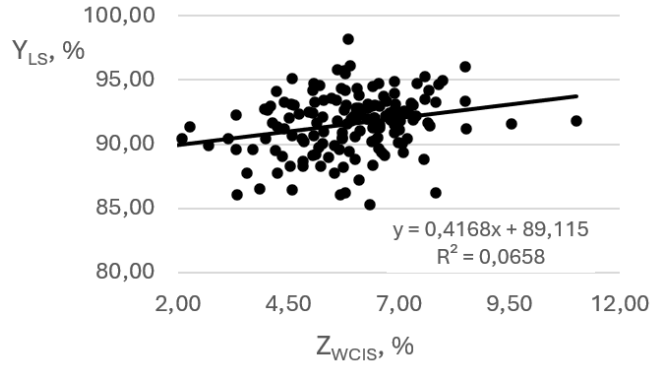


Fig. 7. The impact of the share of WCIS scrap on the liquid steel output

A high carbon potential promotes intensive slag foaming (reduction of iron losses in the slag through the thermodynamic reaction [C] + (FeO) → {CO} + [Fe], which explains the positive trend of the regression line. On the other hand, the need for deep and time-varying oxygen refining to eliminate excess carbon

generates high, stochastic fluctuations. As a result, the final steel yield becomes highly random and depends more on the secondary refining operating procedures and the intensity of the oxygen blast than on the mass fraction of cast iron in the charge.The final key step in the analysis of the charge structure was to examine the effect of the share of ferroalloys designated as WFS class (Z_{WFS}, %) on the liquid steel yield (Y_{LS}, %). The research material included a complete sample of 180 heats, meaning that this component was a constant technological element in each of the analyzed EAF processes. The function determined by linear regression took the mathematical form: $Y_{LS} = 0.9467x + 90.501$. The regression slope a = 0.9467 shows a very high value, close to unity. This suggests that each additional percentage of WFS ferroalloys introduced has a strong, theoretical potential to increase liquid steel yield by nearly 0.95%. Despite such high dynamics of changes, the coefficient of determination is only $R^2 = 0.0402$ (which corresponds to a weak Pearson correlation (r ~ 0.20). This model therefore explains only about 4% of the yield variance. This state is fully justified by the metallurgical and physicochemical conditions of the EAF process. WFS ferroalloys are introduced in relatively small quantities (the graph shows concentration mainly in the range from 0.5% to 1.6% of the charge share), and their primary task is to deoxidize the bath and precisely regulate the chemical composition (setting to the desired steel grade), and not to maximize the mass yield. The high vertical scatter of experimental points (Figure 8) in each of the heats (from about 85% to 96% of the yield) proves that the final yield index is determined by the global scrap structure of the basket and the efficiency of the oxygen and slag refining operations. The share of ferroalloys WFS, although essential for alloy metallurgy, plays a secondary and stochastic role in shaping yield.

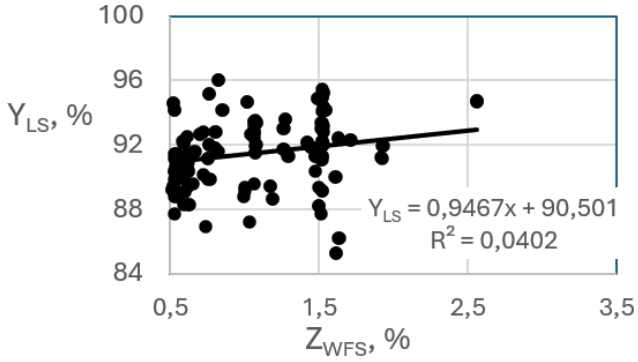


Fig. 8. The impact of the share of WFS scrap on the liquid steel output

3. Summary and Conclusions

A linear regression and correlation analysis of 180 heats smelted in an electric arc furnace (EAF) revealed a highly variable effect of individual metal-bearing charge components on liquid steel yield. Components with high bulk density and low oxidation states, such as grades W1, W18, and W5, exhibit a strong, stable, and positive effect on process efficiency, allowing for precise prediction of metallurgical outcomes. In contrast, light scrap grades (W8, W13), as well as scrap grades W2 and, additionally, WCIS and WFS, are characterized by high randomness and poor fit to linear models. In these cases, the final steel yield is determined not by the mass fraction itself, but by secondary furnace operating procedures, such as oxygen refining dynamics or slag foaming. The statistical analysis considered 30% of the mass of ferroalloys added at the end of the heat. This is because approximately 1/3 of the total mass of ferroalloys is Fe, which complements the chemical composition of the metal bath and thus significantly increases the yield of liquid steel. The remaining mass of ferroalloys, the smallest amount of which is decisively consumed in steel deoxidation and passes into the slag as oxides. Despite the smallest percentage share in the metallic charge, due to its large impact on the yield, this relationship should be considered significant.

Based on the findings of this study, the following conclusions can be drawn:

- Highest Technological Efficiency: Heavy scrap grade W1 and ferroalloys WFS demonstrate the greatest potential for increasing liquid steel yield, achieving regression slopes of 0.91 and 0.95, respectively, for each percentage share in the charge.
- Maximum Process Stability: Steel scrap grade W18 (shredded scrap) is characterized by the highest degree of mathematical fit, $R^2 = 0.6097$, making it the most predictable charge component, minimizing technological risk during industrial steelmaking.
- Passivity of Light Charges: Light scrap grades (W2, W13, and W8) are technologically passive ($R^2 \sim 0$) because their high surface area favors iron oxidation under the electric arc, making the yield a random value.
- Random nature of cast iron scrap: WCIS cast iron scrap, despite a clear positive trend (a = 0.4168), exhibits a weak correlation ($R^2 = 0.0658$), which results from the need for an intensive and time-varying oxygen refining process to remove excess carbon.
- Implementation recommendation from the conducted analysis: To stabilize the process and maximize steel yield from the heat, the structure of the EAF charging baskets should be reconfigured to increase the share of heavy grades (W1, W18) at the expense of fine and contaminated charges (W2, W13).

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