# A DATA-DRIVEN APPROACH TO THE SELECTION OF SUSTAINABLE EMULSIONS FOR COLD-ROLLED STEEL PRODUCTION

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***ABSTRACT**: The use of emulsions in the cold rolling process significantly reduces rolling forces, increases material reduction, and enables the production of thinner final steel products. This enhances the stability and surface quality of the processed material. However, annealing these cold-rolled coils often leads to sustainability challenges due to the formation of surface defects such as soot. These defects are influenced by factors including uneven emulsion application, inadequate surface preparation, and the specific physicochemical properties of the emulsion itself. This study investigates the root causes of soot-related defects in annealed steel coils processed with emulsions, highlighting the necessity of mitigating these issues to ensure sustainable and environmentally friendly production. To achieve this, optimal physicochemical parameters for lubricating and cooling fluids were determined, supporting waste minimization and resource efficiency. A novel testing methodology was introduced to evaluate the tendency of emulsions to produce soot under actual annealing conditions. This process involved applying concentrated emulsions to test samples, annealing them alongside coils in identical furnace conditions, and assessing the soot formation visually. The study analysed 54 emulsions, employing regression models to establish relationships between soot formation and parameters such as density at 20 °C, kinematic viscosity at 50 °C, and saponification number. Advanced mathematical techniques, including regression analysis and correlation evaluation, were utilized to quantify these relationships, ensuring robust conclusions. A significant correlation was identified between the pH of a 3% water-based emulsion and these properties. The Pareto analysis was applied to prioritize the influence of emulsion properties on soot formation, enabling the identification of the most impactful factors for optimization. As a result, 27 sustainable emulsions were recommended for implementation at PJSC "ZAPORIZHSTAL," contributing to lower rejection rates due to surface defects and promoting sustainable practices in rolled steel manufacturing.*

***KEY WORDS**: cold rolling, soot formation, emulsion properties, Pareto analysis, regression equations, sustainable steel production*

## 1 INTRODUCTION

Emulsions play a crucial role in cold rolling of bars and plates, offering numerous advantages such as enhanced energy efficiency during rolling, better lubrication and cooling at contact points, superior surface finish, increased corrosion resistance, and significant environmental and economic benefits (Krivtsova et al., 2013).

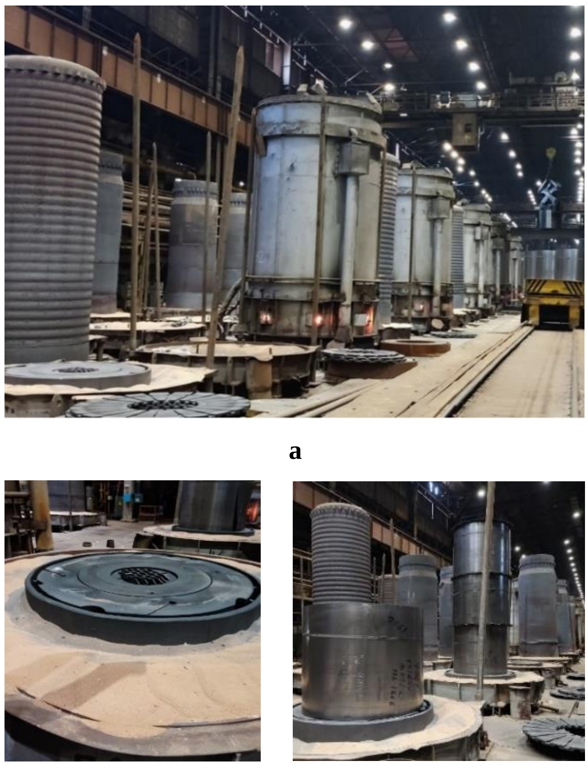
The use of emulsions as lubricants and coolants during the rolling process aims to reduce friction between the metal surface and the rolls. This reduces energy consumption and wear on the rolling tools. Paper (Kukhar et al., 2023) states that the physical, chemical and rheological properties of the emulsion, namely the kinematic viscosity, influence the energy consumption during cold rolling with emulsions on tandem four-high stands. It has been shown that increasing the kinematic viscosity of the rolling emulsion by 10 mm2/s can reduce specific energy consumption by 0.07 kWh/t (0.82%) in a 4-stand mill, by 5.81 kWh/t (1.77%) in a 5-stand mill, and by 4.70 kWh/t (1.54%) in a 6-stand mill (Fujita et al., 2016). Therefore, the energy intensity of the 5-cell mill was found to be higher than that of the 4-stand and 6-stand mills. Studies by the authors of (Fujita et al., 2016; Holz et al., 2011; Aliiev et al., 2024; Marchenko et al., 2020; Shtuts et al., 2020) also indicate the influence of the rheological characteristics of emulsions and process lubricants on friction conditions, energy consumption during deformation, and the presence of residual lubricating and cooling fluids (LCF) on the metal surface as contaminants. Cold rolling with emulsions is carried out on both continuous (Fujita et al., 2016) and reversing (Holz et al., 2011) mills. In (Fujita et al., 2016), an intelligent lubrication management system for preventing chatter in high-speed cold rolling is proposed, which includes balancing the friction coefficients between adjacent stands in a tandem mill and evaluating effectiveness using a dynamic rolling model. In (Holz et al., 2011), SMS Siemag's innovations for enhancing cold rolling efficiency, especially in reversing mills, include the use of lubricants that help control rolling force, reduce friction, and thereby improve strip surface quality and process efficiency. Special devices have been developed to evaluate the effectiveness of technological lubricants in aluminium pressure treatment (Aliiev et al., 2024), with friction stresses determined by measuring the local surface hardness of the hardened layer with indentations left behind. An increase in the bearing surface area and the formation of oil pockets was observed when rolling bronze bushings (Marchenko et al., 2020) with emulsions, which reduces the temperature load on the friction pair. In (Shtuts et al., 2020), experimental research on the rolling-stamping processes of tubular and cylindrical blanks was conducted, where lubricants were employed to facilitate deformation and reduce friction, thereby enhancing surface precision and processing quality. The influence of temperature and force regimes on the rheology of contacting layers was noted in studies (Savchenko et al., 2020; Chakraborty et al., 2023), and the negative role of hydrocarbon thermal degradation at elevated temperatures was established. In addition to deriving temperature-rheology equations for process lubricants, work (Su et al., 2024) shows that high temperatures and water ingress seriously affect the service life of hydrocarbon lubricants, with surface topographic parameters serving as evaluation criteria.

The cooling effect of the lubricant helps control the temperature of the metal, preventing it from overheating (Horák et al., 2010; Mazuru et al., 2017;). Paper (Avdeenko et al., 2018) suggests that the efficiency of cold rolling mainly depends on the quality of metalworking emulsion and its cost. In this case, emulsols are preferred, as they result in the lowest friction coefficient in the deformation zone and are obtained by processing waste from other industries (Avdeenko et al., 2018). The influence of friction conditions and tool radius on the force modes of deformation, with an emphasis on the importance of the structure of the computational apparatus that takes into account the geometry of friction pairs with a lubricating layer, is shown in (Hrudkina et al., 2021). High-speed deformation during rolling is accompanied by the heating of friction pairs, which requires the use of technological emulsions (Sorokatyi et al., 2015). However, to achieve the proper physical properties of hardened metal, it is subjected to annealing (Borokinni et al., 2022; Khrebtova et al., 2022), which requires the use of process lubricants that leave as little thermal degradation waste as possible. In (Khrebtova et al., 2022), a system based on a PID controller was applied to regulate the temperature during annealing of work-hardened steel wire, achieving a stable heating regime with a control error of no more than 1.3%, which maintains the mechanical properties specified by the technological process. The presence of thermal degradation waste and its impact on surface quality when controlling the temperature field of a sheet billet by applying thermally unstable coatings is reported in (Anishchenko et al., 2018). To take into account surface imperfections of sheet blanks during deformation and describe the behaviour of surface defects, it is known to use a mathematical apparatus based on super formulae (Anishchenko et al., 2018), finite element modelling (Moir & Preston, 2002) or the basics of experimental mechanics (Li & Sun, 2013).

In work (Kartun et al., 2020), the expediency of using fullerene-like nanoparticles as a lubricant additive in the composition of MT-216 M technological grease was experimentally proved, with a stable lubricating effect at a concentration of 1.0% FLN in the emulsol. Some emulsions contain additives that help protect the metal from corrosion during and after processing (Al-Sabagh et al., 2012; Nazeer & Madkour, 2018). It should be noted that the above materials may increase soot formation during the post-rolling annealing operation with emulsions. Unlike some other lubricants, emulsions are more environmentally friendly, as they mainly consist of water with the addition of oil (Krivtsova et al., 2013; Fernández et al., 2005) or other lubricants, which reduces the risk of environmental pollution. Paper (Srivastava, 2004) developed planning and technical measures to reduce the disorganised emulsion of emulsol on the surfaces of metal and equipment. A study (Antonicelli et al., 2023) shows the environmental benefits of a "green lubricant" for cold rolling, which is made using biological substances and additives without mineral oils, biocides or other toxic substances. In a study of three different emulsions based on a mixture of oils and water, it was found that emulsions with relatively low stability, larger droplet size and a high saponification number provide better lubrication and a lower coefficient of friction (Dubey et al., 2005). Study (Vergne et al., 1997) also confirmed the effectiveness of using natural ingredients. The use of emulsions and emulsols in cold rolling can also be more favourable in terms of the resulting technical and economic performance compared to some other lubricants due to their relative cheapness and cost-effectiveness in achieving the target effect (Shirizly & Lenard, 1999). Thanks to the developed methodology and studies on 24 emulsions in cold rolling, it was established (Vasilev et al., 2018) that high antifriction and detergent efficiency of modern emulsions is achieved at a kinematic viscosity of 30-45 $mm^2/s$ and an increase in the saponification number to 160-195 mgKOH/g (Kukhar et al., 2023; Vasilev et al., 2018).

The authors of (Sun et al., 2017) indicate that the addition of iron powder to the emulsion improves the antifriction effect. However, any residual powdered emulsions must be thoroughly washed off before annealing and finishing to prevent surface contamination. Experimental studies of emulsion residues on the mill after rolling and numerical modelling revealed the nature of their dependence on the concentration and affinity of emulsion particles to the steel surface of the emulsifier (Azushima et al., 2011). Increasing the amount of residual emulsion increases the contamination of the stack. At the same time, theoretical models based on fluid mechanics and colloid chemistry are known to control the thickness of the lubricant at the entrance to the rolling zone (Curcija & Mamuzic, 2005). In addition, work (Curcija & Mamuzic, 2005) pays considerable attention to the means of removing process lubricants from the metal surface (to prevent contamination) and the environmental problems of using emulsions. Hybrid lubrication systems are used to control the lubrication process and the formation of a lubricating film during high-speed rolling (Kimura et al., 2015). Report (Aries et al., 2022) analyzes the technology of manufacturing galvanised steel in cold rolling mills and draw attention to the fact that the emulsion must be well washed off before annealing and pickling. The appearance of the soot defect, which is associated with emulsol residues in coils after annealing, is mentioned in (Rentz et al., 1999; Saravanan & Srikanth, 2018).

Thus, among the main factors affecting the deterioration of emulsion washout conditions and the occurrence of surface contamination, which turns into soot at the technological stage of coil annealing in furnaces, are the concentration, viscosity and saponification number of emulsions. In the cold-rolling shop of PJSC "ZAPORIZHSTAL", annealing is carried out in bell furnaces with a protective atmosphere of pure hydrogen from Ebner and in bell furnaces with a protective atmosphere of HNx gas (Fig. 1).



a

b c

**Fig. 1 HNx gas bell-furnaces at the cold rolling mill of PJSC "ZAPORIZHSTAL": furnace span of the shop (a); hearth with a sand gate (b); coil laying before covering with a cap (c)**

The aim of the study was to identify emulsifiers from the list of available products of the cold rolling shop of PJSC “ZAPORIZHSTAL”, which can be recommended for cold rolling to minimise rejection of coils due to soot defect after annealing in the open-hearth furnaces, taking into account the effect of the above-mentioned main factors.

## 2 RESEARCH METHODOLOGY

The quality of rolling emulsions plays a critical role in determining the surface condition of cold-rolled steel and mitigating surface defects such as soot, emulsion burns, and dirt marks. To address these issues, reduce friction, minimize wear on work rolls, and enhance cooling efficiency during cold rolling, emulsions from various manufacturers were tested. Currently, emulsions are utilized in two main applications: (a) oiling pickled hot-rolled coils, where the emulsion is applied during the coiling process on the NTA-4 continuous pickling line using an electrostatic oiling machine; and (b) in cold rolling operations on both continuous 4-stand mills and reversing mills.

For cold rolling, emulsion is used in the form of a solution (diluted in demineralised and/or process water at a concentration of 1.5-4.0%). For the experimental conditions, an emulsol concentration of 3% was used in all cases. For the conditions of each specific production, taking into account the composition of the process equipment, a different type and brand of emulsol is developed and implemented. Each emulsion sol designed for use in cold rolling has several key components, which are selected based on the operating conditions of the process emulsion, the specifics of the rolling mill emulsion system, the emulsion magnetic cleaning system, etc.

In the cold rolling shop of PJSC “ZAPORIZHSTAL”, various brands of emulsions from different manufacturers were tested. Testing was conducted in 4 stages: Stage 1 - Laboratory tests on emulsion soot formation; Stage 2 - Pilot tests on reversing mill 1680 (1.5 to 2 tonnes of emulsion was provided for stage 2); Stage 3 - Pilot tests on continuous 4-stand mill 1680 (10 tonnes of emulsion was provided for stage 3); Stage 4 - Extended tests for 3 months on all rolling mills. The first stage, laboratory tests on soot formation of emulsions, is considered in this paper. Staged testing is designed to minimise the risk of delivering emulsion that is unsuitable for the equipment, and to minimise scrap and order delays due to rejection for defects in the rolled emulsion. Laboratory tests of emulsions included determining the product's main physical and chemical characteristics. The following is a discussion of these physical and chemical properties and the methods used to determine them.

The appearance was determined visually. For this purpose, the emulsion was poured into a 100 ml cylinder and viewed under transmitted light. The indicator describes the appearance of the product, its purity, and the presence of sediment. Appearance is important in describing the consistency, homogeneity, colour, and transparency of the coolant. Fresh coolant is usually an oily, clear liquid from light yellow to dark brown. During operation, under the influence of oxidation and contamination, the coolant darkens, loses its transparency and sometimes even homogeneity. The dark colour of the coolant and its heterogeneity indicate its overheating, oxidation and contamination.

Odour as an indicator is important for the operation of the rolling emulsion. It depends on the coolant's composition and can characterise changes in its quality during storage and operation. Most oil-based coolants have a specific smell of petroleum oil used as their base. During operation, the coolant is subject to contamination, mixing with other lubricants and the action of microorganisms. As a result, its odour changes. Coolant with a persistent unpleasant odour, even with good basic performance (ability to extend tool life and improve the quality of machined products), is not acceptable to use and should be replaced.

The density at 20 °C, g/cm$^3$, was determined according to GOST 3900 (Interstate Standard). The density of the coolant was used to determine the chemical nature of the petroleum-based oil used to make the fluid. Of the three main groups of hydrocarbons (with approximately the same molecular weight) present in petroleum oil, aromatic hydrocarbons have the highest density, and paraffinic hydrocarbons have the lowest density.

The kinematic viscosity at 50 °C, mm$^2$/s, was determined according to GOST 33 (ISO 3104, International Standard). Kinematic viscosity ($\nu$), or the coefficient of internal friction, is a ratio of dynamic viscosity to density of a fluid at a given temperature: $\nu = \eta / \rho$, where $\eta$ is dynamic viscosity and $\rho$ is fluid density. The kinematic viscosity of the coolant is determined by employing capillary glass viscometers. The viscosity decreases with rising temperature and increases with falling temperature. The less the coolant changes its viscosity with temperature, the higher its quality. High viscosity oil coolants provide better lubrication and reduce vibrations of the cutting tool. At the same time, the high viscosity of the coolant impairs the cleaning and cooling effect. It also prevents rapid sludge settling out of the liquid during settling and cleaning. All this necessitates the selection of the optimal coolant viscosity.

The saponification number, mgKOH/g, was determined according to GOST 21749 (Interstate Standard). The saponification number of a process lubricant during cold rolling is an indication of whether or not the process lubricant has good lubricating and cleaning properties. This is because fatty acids, which are the main part of vegetable and animal fats, are the substances that determine the lubricating ability of a lubricant. The saponification number also determines how easily contaminants can be removed from the strip surface. After rolling, a certain amount of lubricant remains on the strip and must be removed before coating or annealing.

The mass fraction of water, %, was determined according to GOST 2477 (Interstate Standard). Oil-based coolants have a hygroscopicity that depends on the temperature of the fluid and the ambient air environment. At 20 °C, approximately 0.003 % (wt.%) of water dissolves in oil coolants. As the air temperature and coolant temperature change, water vapour in the air can condense. As a result, moisture diffuses into the coolant. Also, depending on the coolant temperature, there is always a small amount of dissolved air containing moisture.

Emulsion stability is the most important factor in coolant efficiency. That is, the higher it is, the longer the liquid prepared from the concentrate will last and the more efficiently it will work. Stability can be determined using the Stokes equation. It is determined by the difference in density between the oil phase and water. If the density of the oil is close to the density of water, we can speak of a higher resistance of the coolant. The viscosity of the environment and the gravitational constant are also of great importance (here we can talk about a direct proportion). The higher the viscosity of an oil or emulsion, the more stable it is. Emulsions made from concentrates based on virgin oils show high stability. If used oil is included, the end product does not have a long service life. The degree of stability of the emulsion can be determined by means of special equipment or by eye. The higher it is, the longer the finished mixture does not delaminate and the longer it retains its original appearance. Unstable coolants cannot be used for a long time, as they lose their properties over time, so this factor is important.

Ash content was determined according to GOST 1461 (Interstate Standard). This is the residual ash content of the emulsion after it has been burned. Ash content indicates the amount of mineral and metal deposits that can form during operation.

The pour point, ºC, is the lowest temperature at which the oil spreads under the influence of gravity. The concept of pour point is used to determine the ability of oil to be pumped through pipelines and the ability of oil to lubricate friction units that operate at low temperatures. The pour point of an emulsion is the temperature at which the emulsion, placed in a test tube and tilted at an angle of 45°, does not change its level within one minute. The pour point should be 5...7 °C lower than the temperature at which the emulsion is to be rolled. Emulsion fluidity must be maintained to allow emulsion preparation and addition at low temperatures. The indicator was tested according to GOST 20287 (Interstate Standard).

Electrostatic application is the ability of an emulsion to be applied in an electrostatic field in an electrostatic oiling machine installed on the continuous pickling unit BTA-4 in the cold rolling mill of PJSC "ZAPORIZHSTAL". Not all products have this capability. An emulsion that is not designed for this purpose can damage the electrostatic lubricant. This was requested from the Emulsol supplier and subsequently verified when testing.

The hydrogen pH of a 3% water-based emulsion prepared with hard water of 4.6 mg-eq/dm$^3$ is an indicator of the emulsion`s acidity. At high pH levels, the oils emulsify better and generally produce a more stable emulsion. The greater the emulsion stability (coolant), the smaller the oil droplet size in the emulsion, and the lower the level of lubricating properties.

The corrosive effect of the water emulsion was determined according to GOST 6243 (Interstate Standard). Corrosion of metals, resulting from chemical or electrochemical reactions induced by lubricating and cooling media, was evaluated by immersing a steel plate into the tested product. The product successfully passed the corrosion test if no visible spots or stains were observed on the plate's surface upon visual inspection.

Storage stability, defined as the emulsion's ability to retain its properties when prepared in hard water (4.6 mg-eq/dm$^3$) over six hours, was determined following GOST 6243 standards. The evaluation involved exposing the emulsion to alternating high and low temperatures, followed by centrifugation to assess the extent of stratification.

The soot and carbon formation tendency of a 4% water-based emulsion was determined in points following the "Instructions for the study of coolants for resistance to soot and carbon formation of the emulsion during annealing in laboratory conditions" (PJSC "ZAPORIZHSTAL"). The laboratory tests were used to determine the supplier's ability to meet the performance indicators stated in the regulatory documents, as well as to determine at the first stage the suitability of the emulsion for a particular production.

A special practical research methodology was developed to determine the soot formation tendency of emulsol. The experimental emulsion (concentrate) was applied to two samples (Fig. 2) of 150×150 mm in size from cold-rolled metal, the samples were stacked together and fixed in a brace (Fig. 3), after which they were annealed in a gas cap furnace in an atmosphere of protective HNx gas.

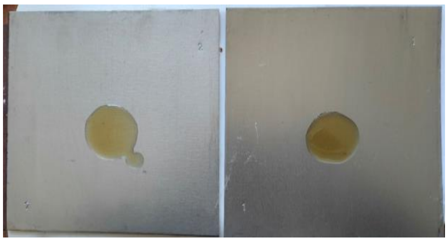


**Fig. 2 Samples with emulsol concentrate applied**

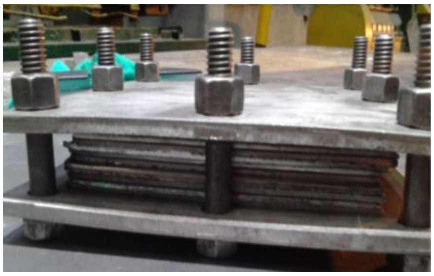


**Fig. 3 Brace with samples**

The brace was attached (Fig. 4) with the packing tape to the bottom edge of the coil so that the end of the brace was parallel to the roll coils. Before packing, the stand was checked for leaks to prevent any negative external factors from affecting the experiment. After annealing, the brace is opened and the surface of the samples is evaluated on a scale of 0...5 points (Fig. 5). If the score exceeds 3 points, the emulsion is considered prone to soot formation and is not recommended for further testing.

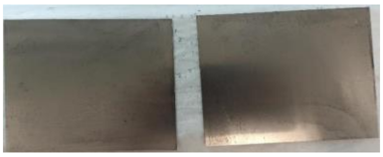
**Fig. 4 Brace attached to the coil**

Practical experience has shown that an emulsion with a low saponification number (up to 50 mgKOH/g) is prone to soot formation if it gives a burn value above 1. An emulsion with a high saponification number (over 50 mgKOH/g) is prone to soot formation if it gives a burn value above 3.

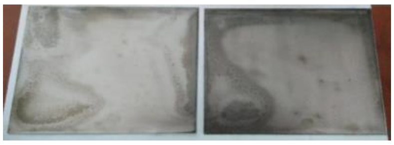
## 3 RESULTS AND DISCUSSION

A total of 54 emulsions underwent laboratory testing, each displaying distinct physical and chemical properties, as outlined in Table 1. Following these evaluations, 27 emulsifiers were selected as suitable candidates for pilot testing. The detailed results of these laboratory investigations are presented in Table 1.

The selection of products for pilot testing on a reversing mill was guided by expert analysis, utilizing the findings and insights from the laboratory studies. These initial tests allowed for a thorough examination of the dataset (Table 1) to identify emulsions unsuitable for further trials. This approach minimized the risk of product rejections and mitigated potential losses during industrial-scale testing (Kruzhilko et al., 2021).



**soot formation with score 0 points**



**soot formation with score 1 points**

**soot formation with score 2 points**

**soot formation with score 3 points**

**soot formation with score 4 points**

**soot formation with score 5 points**

**Fig. 5. Soot formation scale (in points)**

**Table 1. Results of laboratory tests of emulsions (actual values)**

| Seq. N | Initial data | | | | Outcome | | | |
|---|---|---|---|---|---|---|---|---|
| | Brand of emulsol | Density at 20 °C | Brand of emulsol | Density at 20 °C | Brand of emulsol | Density at 20 °C | Brand of emulsol | Density at 20 °C |
| | name | [g/cm3] | [mm2/s] | [mgKOH/g] | score | [pH] | score | +/– |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| - | - | X1 | X2 | X3 | Y1 | Y2 | Y3 | - |
| 1 | Rolling oil | | | | | | | |
| 2 | Lubro DL ZPS | 0.900 | 26.19 | 94.30 | 3 | 3.81 | 2 | + |
| 3 | Rolling oil | | | | | | | |
| 4 | TRENOIL S740 | 0.915 | 30.26 | 171.14 | 3 | 3.56 | 2 | + |
| 5 | QH EVEROLL S1650 ZP | 0.915 | 38.03 | 133.57 | 3 | 3.97 | 2 | + |
| 6 | YUKO Lubrinol-2M | 0.916 | 43.02 | 27.49 | 0 | 8.26 | 2 | + |
| 7 | TRENOIL SCR 145 | 0.92 | 34.82 | 160.44 | 3 | 3.67 | 3 | + |
| 8 | Condor-Roll 4001 | 0.903 | 15.6 | 124.50 | 1 | 4.82 | 3 | – |
| 9 | KRONOL 163UA-11 | 0.922 | 39.63 | 136.03 | 4 | 5.54 | 3 | – |
| 10 | KRONOL 163UA-12 | 0.92 | 39.61 | 135.79 | 4 | 5.45 | 3 | – |
| 11 | Universal-1TS modified | 0.924 | 35.56 | 94.85 | 3 | 7.56 | 3 | – |
| 12 | AZMOL Delta Ecoline MN mark 1 | 0.901 | 19.53 | 91.54 | 3 | 4.7 | 3 | + |
| 13 | ROLLUB 988-AR | 0.921 | 28.67 | 141.6 | 3 | 4.4 | 3 | + |
| 14 | Finerol-159 M | 0.912 | 31.26 | 143.14 | 3 | 5.8 | 1 | + |
| 15 | Quakerol ZAP 4.0 | 0.927 | 40.58 | 164.44 | 3 | 3.8 | 0 | + |
| 16 | Quakerol ZAP 3.0 | 0.93 | 42.92 | 174.3 | 3 | 4 | 2 | + |
| 17 | Hydroway O | 0.908 | 14.9 | 90.35 | | 8.45 | 1 | + |
| 18 | Hydroway 840 | 0.901 | 13.02 | 126.27 | | 8.72 | 1 | + |
| 19 | Universal-1TS | 0.894 | 20.2 | 68 | 1 | 8.5 | 1 | + |
| 20 | UHV brand A | 0.906 | 28.58 | 72.42 | 2 | 9.4 | 1 | + |
| 21 | Cold Roller S (synthetic) | 1.064 | - | - | - | 8.72 | - | + |
| 22 | Azmol | | | | | | | |
| 23 | Aquanol M | 0.921 | 25.29 | 85.06 | 4 | 8 | - | – |
| 24 | Azmol | | | | | | | |
| 25 | Aquanol D | 0.897 | 55.53 | 13.58 | 2 | 9.2 | 1 | + |
| 26 | Universal-TS | 0.92 | 34.07 | 33.67 | 1 | 9 | 2 | + |
| 27 | Azmol OM | 0.895 | 31.2 | 25.3 | - | - | | + |
| 28 | Emulsol T | 0.874 | 20.1 | 21.2 | - | - | 1 | – |
| 29 | Quakerol ZAP-ST 1.0 (topical) ZAP-ST 1.0 (topical) | 0.894 | 36 | 83.6 | - | 4.5 | 0 | – |
| 30 | Quakerol-405 | 0.890 | 37.3 | 81.0 | - | - | 0 | – |
| 31 | Agrinol OM | 0.899 | 22.3 | 27 | - | - | 1 | + |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 32 | Gerolub 5543-1 | 0.926 | 36.77 | 135.13 | - | 8.5 | 1 | + |
| 33 | Cold Roller | 0.894 | 20.2 | 68 | - | 8.5 | 0 | + |
| 34 | BONDERITE | | | | | | | |
| 35 | L-RO 5529-4 | 0.92 | 21.89 | 191.44 | - | 5.2 | 2 | – |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 36 | Rolkleen EP 2720 ILY (local) | - | 9.18 | 14.9 | - | 8 | 2 | – |
| 37 | AVIKS BIOM | 0.922 | 27.5 | 91.57 | - | 8.2 | 2 | – |
| 38 | RI-LAMIN | | | | | | | |
| 39 | MM-1680/ZPS | 0.927 | 34.47 | 180.18 | - | 6.3 | 4 | – |
| 40 | Rolkleen | | | | | | | |
| 41 | EP 2744 SCH | 0.908 | 22.11 | 168.81 | - | 3.9 | 2 | + |
| 42 | YUKO Lubrinol-M (ISO 46) | 0.899 | 28.39 | 69.41 | 2 | 8.2 | 1 | – |
| 43 | BONDERITE | | | | | | | |
| 44 | L-RO 3515-3 | 0.918 | 35.37 | 99.72 | - | 5.3 | - | – |
| 45 | Unisol | 0.901 | 25.01 | 64.91 | - | 8.2 | 3 | – |
| 46 | MOL Emroll SCR | 0.892 | 30.31 | 30.89 | - | 7.6 | - | + |
| 47 | Rolkleen | | | | | | | |
| 48 | EP 2744 SCH | 0.909 | 31.36 | 175.87 | - | - | - | + |
| 49 | Universal TS brand A | 0.885 | 26 | 27.8 | - | - | 3 | – |
| 50 | EX-AM RUP | - | - | - | - | - | 4 | – |
| 51 | ENTEX EM | 0.9 | 33.5 | 22.97 | - | - | 1 | – |
| 52 | Ivaprol-2 | 0.882 | 18.0 | 50.0 | - | 9 | 2 | + |
| 53 | Gerolub-5548 | 0.923 | 34.46 | 154 | - | 5.7 | 0 | – |
| 54 | SUV-1 | 0.904 | 50 | 40 | - | 9 | 1 | – |

Notes:
* 3% water-based emulsion prepared in hard water 4.6 mg-eq/dm$^3$
** "+" – recommended;"–" – not recommended

As a result of processing the data in Table 1, the following regression equations were obtained: mathematical dependences on the initial data of the indicator (in points) of plate annealing in a brace with the applied concentrate ($Y_1$), the hydrogen pH of a 3% water emulsion prepared with hard water of 4.6 mg-eq/dm$^3$ ($Y_2$), and the indicator of the tendency to soot and burn formation of a 4% water emulsion ($Y_3$):

$$Y_1 = -7.194 + 8.67X_1 + 0.013X_2 + 0.013X_3; \; (1)$$
$$Y_2 = -34.669 + 51.372X_1 - 0.054X_2 - 0.037X_3; \; (2)$$
$$Y_3 = -28.454 + 33.255X_1 - 0.014X_2 + 0.002X_3, \; (3)$$

where $X_1$ is the density at 20 °C, g/cm$^3$; $X_2$ is the kinematic viscosity at 50 °C, mm$^2$/s; $X_3$ is the saponification number, mgKOH/g.

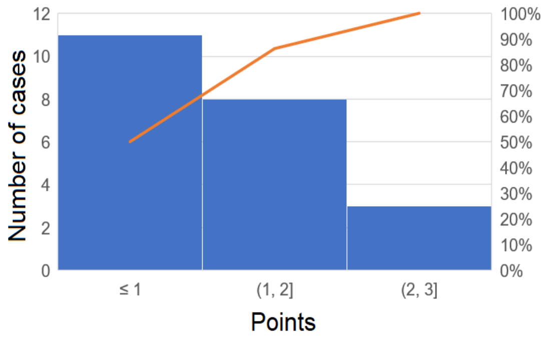
The calculations using formulas (1) and (3) give fractional values (they do not give whole numbers equal to points), so the results should be rounded up to the nearest point. It is possible to select variants of characteristics $X_1$, $X_2$, and $X_3$ that give the desired values of $Y_1$, $Y_2$, and $Y$3 by viewing expressions (1)-(3) as a system of three equations with three unknowns. The results of this selection are summarized in Table 2.

Characteristics $X_1$, $X_2$, and $X_3$ were evaluated using the Pareto principle to develop recommendations for emulsion characteristics that would not result in increased soot formation during annealing. Only those values whose aggregate resulted in a "+" were selected as a recommendation for further use, and the data for the rows corresponding to certain emulsols were complete.

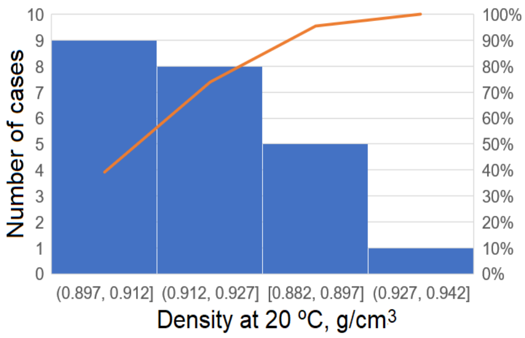
**Table 2. Examples of the system of equations (1)-(3) for selecting the properties of emulsions**

| Option | 1 | 2 | 3 |
|---|---|---|---|
| Characteristics of emulsol (X) | X1 = 0.932<br>X2 = 45.15<br>X3 = 40.27 | X1 = 0.925<br>X2 = 41.02<br>X3 = 125.93 | X1 = 0.948<br>X2 = 22.91<br>X3 = 129.19 |
| Expected result (Y) | Y1 = 2<br>Y2 = 9.3<br>Y3 = 2 | Y1 = 3<br>Y2 = 6<br>Y3 = 2 | Y1 = 3<br>Y2 = 8<br>Y3 = 3 |

Accordingly, the impact on soot formation was assessed using the $Y_3$ parameter. Thus, for the evaluation of $X_1$, 23 emulsions were included in the specified conditions, for the evaluation of $X_2$ and $X_3$ – 22 emulsions from Table 1. Pareto diagrams are shown in Figures 6–8.

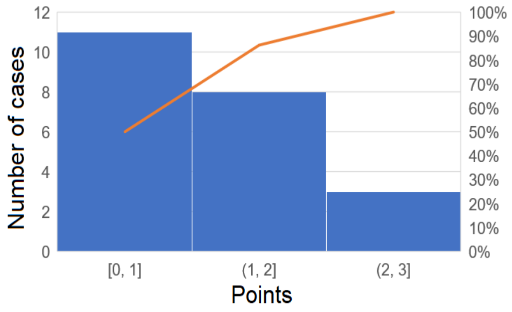



a

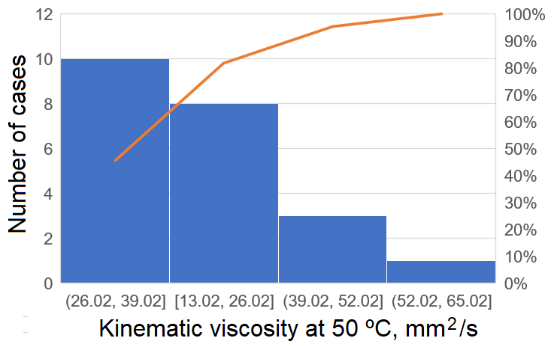



b

**Fig. 6 Influence of density characteristics (X1) on the soot formation tendency of emulsol (Y3): distribution of soot formation scores points (a); distribution of density values, g/cm3 (b)**

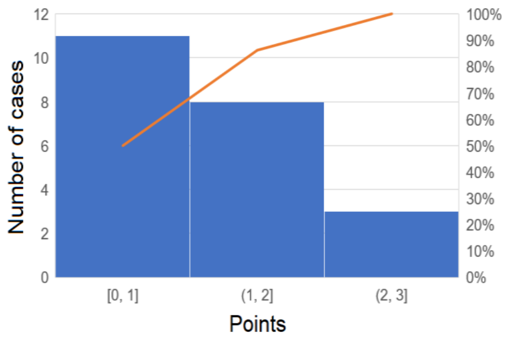



a

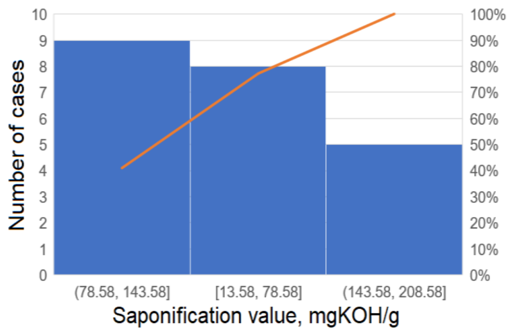



b

**Fig. 7 Influence of kinematic viscosity characteristics at 50 °C on the soot formation tendency of emulsol (Y3): distribution of soot formation scores points (a); distribution of kinematic viscosity at 50 °C, mm2/s (b)**




a




b

**Fig. 8 Influence of saponification number characteristics (X3) on the soot formation tendency of emulsol (Y3): distribution of soot formation scores points (a); distribution of saponification number values, mgKOH/g (b)**

Requirements for key physical and chemical properties of emulsol for cold rolling were formulated based on the analysis:

- are required to comply with sanitary regulations;
- are required to be suitable for electrostatic oiling;
- should not have a pungent odour;
- should be homogeneous and free of clots, flakes and sediment;
- should easily evaporate from the strip surface without forming defects during subsequent heat treatment and should not have a corrosive effect on the strip.

## 5 CONCLUSIONS

The study highlights the critical importance of emulsions in the cold rolling process and addresses the problem of surface defects like soot formation during the annealing of emulsion-coated coils. Through extensive testing of 54 emulsions from various manufacturers used in cold rolling at PJSC “ZAPORIZHSTAL,” the research identified the primary factors contributing to soot defects. The analysis established relationships between soot and carbon residue and key physicochemical properties, including emulsol density at 20 °C, kinematic viscosity at 50 °C, and saponification number. Regression models were developed to quantify these relationships, providing a robust mathematical foundation for understanding the behavior of emulsions under operational conditions. Based on the findings, 27 emulsions were recommended as suitable for production, with specific requirements for their physical and chemical properties to ensure optimal performance. The study employed Pareto analysis to prioritize the influence of emulsion characteristics on soot formation, identifying the most significant factors. These insights enabled the formulation of precise recommendations to reduce the incidence of defects after annealing. Overall, the results contribute to improving coil quality and achieving more sustainable and efficient cold rolling practices.

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