ENGINEER

international scientific journal

ISSUE 1, 2025 Vol. 3
E-ISSN
3030-3893
ISSN
3060-5172

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TOSHKENT DAVLAT TRANSPORT UNIVERSITETI
Tashkent state transport university

ENGINEER

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E-ISSN: 3030-3893

ISSN: 3060-5172

VOLUME 3, ISSUE 1

MARCH, 2025

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TASHKENT STATE TRANSPORT UNIVERSITY

ENGINEER

INTERNATIONAL SCIENTIFIC JOURNAL
VOLUME 3, ISSUE 1 MARCH, 2025

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Tashkent State Transport University had the opportunity to publish the international scientific journal “Engineer” based on the **Certificate No. 1183** of the Information and Mass Communications Agency under the Administration of the President of the Republic of Uzbekistan. **E-ISSN: 3030-3893, ISSN: 3060-5172.** Articles in the journal are published in English language.

Influence of sulphur on mechanical properties of foundry steels and ways to minimise it

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Abstract: The influence of sulphur on mechanical properties of foundry steels used for the production of highly responsible parts of railway transport has been investigated. It is shown that the sulphur content in steels above 0.025% leads to a sharp decrease in their strength, impact toughness and ductility, which significantly reduces the operational durability of castings. Studies have been carried out to determine the critical limit of sulphur content, at which the properties of steel remain at an acceptable level. On the basis of the obtained data effective technologies of steel desulphurisation have been proposed, which can be introduced in foundry production, in particular, in conditions of Tashkent LMP.
Keywords: foundry steel, ITP, sulphur, non-metallic inclusions, mechanical properties

1. Introduction

Foundry production in Uzbekistan plays a key role in providing machine-building complex with billets, and its development directly depends on the growth rate of machine-building in general. Unlike billets obtained by metal forming (rolled, stamped, forgings), castings retain all the disadvantages and peculiarities of melting and casting, which further affect the properties of finished cast products.

One of the main problems in foundries is the use of outdated regulatory and technical documents, where the levels of harmful impurities in steels do not meet the modern requirements of steel casting metallurgy. Foundry production ensures the manufacture of workpieces of complex geometry with minimal material losses, which makes it one of the key processes in mechanical engineering and metallurgy. However, the quality of castings is largely determined by the content of harmful impurities such as sulphur, phosphorus and oxygen. These elements, even in small quantities, can significantly degrade the mechanical properties of the metal, such as strength, ductility and impact toughness.

Nowadays the problem of sulphur content control in foundry steels is especially urgent. Sulphur, as a non-metallic element, is highly soluble in liquid iron, but when the metal solidifies, it forms sulphide inclusions (e.g. FeS) that precipitate at grain boundaries. This leads to a reduction in the ductility and impact toughness of the steel, and increases the risk of defects such as redbreakage (brittleness at high temperatures). In addition, sulphide inclusions impair the metal's machinability and corrosion resistance.

The influence of sulphur is particularly critical in steels used for the manufacture of critical parts, such as railway components, where high reliability and durability are required. Therefore, control of sulphur content and development of effective methods of its removal (desulphurisation) are important tasks of modern metallurgy.

Modern GOSTs and international standards regulate the maximum sulphur content in steels at the level of 0.010-0.025%. However, foundries often have difficulties in achieving these values due to the use of outdated equipment and insufficient efficiency of steel cleaning methods. This paper discusses methods of steel desulphurisation, their effect on mechanical properties and possible ways of implementation in industrial production. However, the main difficulty lies in the fact that foundries produce small volumes of steel, and the introduction of expensive equipment used in large-scale metallurgy (e.g., vacuum degassers, furnace-ladle units, etc.) to improve quality is practically impossible. The use of such devices significantly increases the cost of castings and leads to long payback periods.

Improved performance and mechanical characteristics of the casting are possible if harmful impurities such as sulphur, phosphorus, gases, non-metallic inclusions and others are effectively removed from the metal. The quality of the casting depends to a large extent on low sulphur content in the final metal.

Sulphur is a non-metallic element that:

Easily dissolves in liquid iron.

Virtually insoluble in the solid state.

According to studies [1, 2], sulphur has unlimited solubility in liquid iron and very low solubility in solid iron. At 1365°C, the limiting solubility of sulfur in u-iron is from 0.04% to 0.05%, and it decreases with decreasing temperature (in the temperature range from 1365°C to 915°C during the transition of u-iron to a-iron). The transition to a-iron causes a sharp formation of sulphides, the concentration of sulphur in iron decreases to 0.01%, and its content continues to decrease with further cooling. Excessive sulphur content, exceeding the solubility limit, leads to a phenomenon called red-brittle (metal fracture). This is especially pronounced in the cast state, where sulphide inclusions are deposited on the boundaries of primary crystallites, which reduces the strength, ductility and toughness of both the metal itself and finished products from it (castings, ingots).

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2. Material and research methodology

The studies were carried out on 20GL casting steels melted in induction crucible furnaces ICF-6 with the main lining at the LMP in Tashkent. The following methods were used for analyses:

Determination of chemical composition of metal by spectral analysis method;

Mechanical tests for tensile, impact toughness and hardness;

Microscopic studies of metal structure and non-metallic inclusions;

Statistical analysis of sulphur content at different stages of production.

Sulphur in steel is mainly present in the form of sulphides (FeS, MnS), which are distributed at grain boundaries and lead to brittleness of the metal. The most dangerous phenomenon is red brittleness - metal fracture when heated above 900°C due to the formation of FeS-Fe eutectic, which has a low melting point (988°C).

As a result of the conducted research it was found that:

When the sulphur content is above 0.025%, the impact toughness of steel decreases by 60-70% at -60°C.

Tensile strength of steel decreases by 8% on average.

The ductility (relative elongation) drops by 50% when the sulphur content increases from 0.013% to 0.043%.

Increased sulphur content reduces the fatigue strength of steel by 1.5-2 times.

Methods of sulphur content reduction

1. desulphurisation technologies

Desulphurisation is the process of removing sulphur from steel, which can be carried out by various methods.

A) Effectiveness of different deoxidising agents in desulphurisation process

The diagram (Fig. 1) shows the effectiveness of different deoxidising agents in the desulphurisation process of steel. It can be seen that calcium and magnesium are the most effective deoxidisers, significantly reducing the sulphur content of steel. Aluminium and silicium also contribute to desulfurisation, but their efficiency is lower.

Key Observations:

1. Calcium reduces sulphur content by 70-80%.
2. Magnesium reduces sulphur content by 60-70%.
3. Aluminium reduces sulphur content by 30-40%.
4. Silicea reduces sulphur content by 20-30%.

The effectiveness of deoxidisers depends on their chemical activity and ability to form stable compounds with sulphur. Calcium and magnesium are highly active and form sulphides (CaS, MgS), which are easily removed to slag. Aluminium and silicium are less active but can also bind sulphur, although to a lesser extent.

Reaction formulas:

Reaction with calcium:

$$Ca+S \rightarrow CaS$$

Reaction with magnesium:

$$Mg+S \rightarrow MgS$$

Reaction with aluminium:

$$2Al+3S \rightarrow Al_2S_3$$

Reaction with silicium:

$$Si+2S \rightarrow SiS_2$$

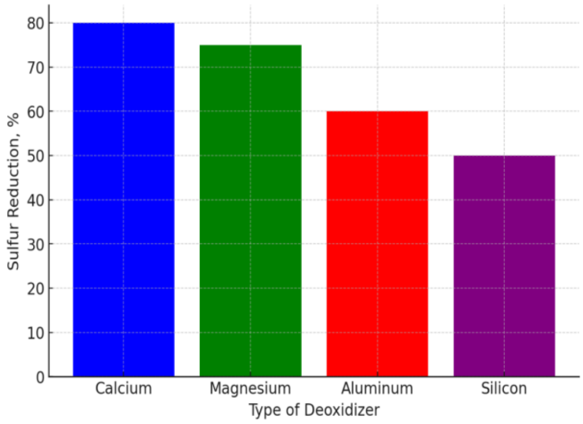

Fig. 1. Effectiveness of different deoxidising agents in the desulphurisation process

B) Basic formulae of desulphurisation

Equilibrium distribution of sulphur between metal and slag

$$L_s = \frac{\%S_{met}}{\%S_{slag}}$$

Where:

L_S - sulphur distribution coefficient,

$\%S_{met}$ - sulphur content in metal,

$\%S_{slag}$ - sulphur content in slag.

Desulphurisation reaction involving calcium

$$Ca + S = CaS$$

where: Calcium (Ca) binds sulphur (S) into a stable compound calcium sulphide (CaS), which is removed to the slag.

Desulphurisation reaction involving magnesium

$$Mg + S = MgS$$

where: Magnesium (Mg) also actively binds sulphur to form MgS.

Kinetics of sulphur removal during vacuumisation process

$$\frac{dS}{dt} = -k[S]$$

where: dS/dt is the rate of sulphur reduction,

k - reaction rate coefficient,

[S] - current sulphur content in the metal.

Steel processing outside the furnace

Methods include: Vacuuming.

Processing of metal in furnace-ladle units.

Introduction of modifiers into the metal to bind sulphur into stable compounds. Figure 2 shows the scheme of the desulphurisation process using synthetic slags. This process includes consecutive stages: addition of deoxidising agents, binding of sulphur into sulphides, slag formation and its removal. This approach allows to effectively reduce the sulphur content in foundry steels, which significantly improves their mechanical properties.

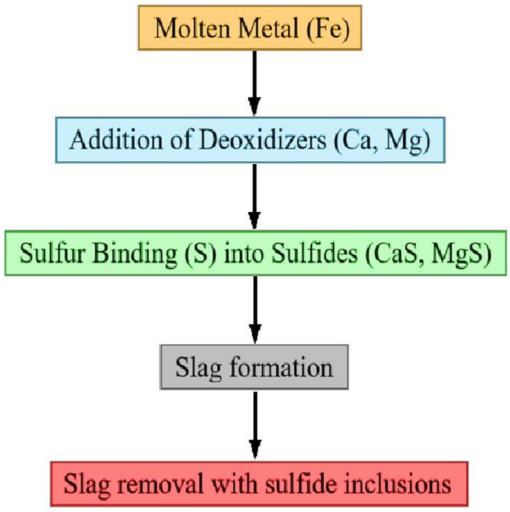

Fig. 2. Scheme of desulphurisation process using synthetic slags

Control of raw materials

Sulphur content reduction is possible at the raw material preparation stage, including the use of high-quality ores and carbonaceous additives.

Influence of temperature on desulphurisation

Dependence of sulphur content in steel on melting temperature

The diagram (Fig. 3) shows the dependence of sulphur content in steel on melting temperature. It can be seen that as the melting temperature increases from 1400°C to 1700°C, the sulphur content of the steel decreases. This confirms that high temperatures promote more efficient desulphurisation.

Main observations:

At 1400°C, the sulphur content is about 0.040%.

When the temperature is increased to 1600°C, the sulphur content decreases to 0.020%.

When the temperature is further increased up to 1700°C, the sulphur content reaches the minimum values of 0.010% and below.

The efficiency of desulphurisation at high temperatures is explained by the following factors:

Acceleration of chemical reactions: Higher temperatures increase the rate of reactions between sulphur and deoxidising agents (e.g. calcium or magnesium), which favours the formation of sulphides (CaS, MgS) and their removal to the slag.

Improved slag mobility: High temperatures make the slag more liquid, which facilitates its interaction with sulphur and its removal from the metal.

Increased sulphur solubility in the slag: At high temperatures, sulphur dissolves better in the slag, which facilitates its more efficient removal.

Reaction formulas:

Reaction with calcium:

$$Ca + S \rightarrow CaS$$

Reaction with magnesium:

$$Mg + S \rightarrow MgS$$

Reaction with lime (CaO):

$$CaO + S \rightarrow CaS + O$$

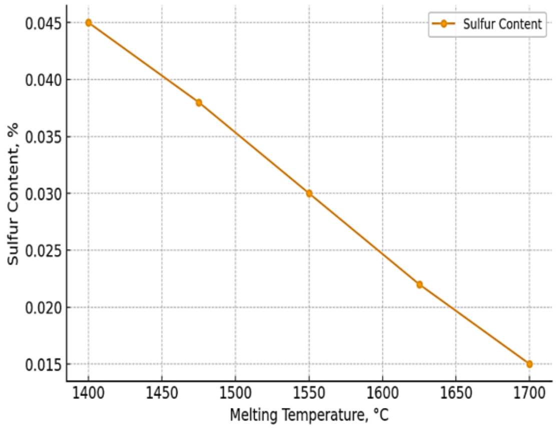

Fig. 3. Dependence of sulphur content in steel on melting temperature

Reduction of sulphur content in metal significantly depends on the melting temperature. The higher the temperature, the faster the desulphurisation processes occur, especially when using active slags and deoxidizers.

Properties were determined in the heat treated state, i.e. after normalisation at (H) 880-890°C;

Statistical analysis of steel melting for sulphur content in the metal during melting and in the liner, as well as analysis of the influence of sulphur on the mechanical properties of steel was made in Excel.

3. Results and discussion

When melting 20GL steel in an induction furnace, the largest number of melts, more than 60%, is characterised by sulphur concentration in the melt from 0.021 to 0.030% by mass. The values of sulphur content in the range of 0.040-0.050%, close to the upper limit of GOST, are about 6%, which is 10 times less than for the above-mentioned values. The largest share of smelts (more than 73.0%) has sulphur content in finished metal in the range from 0.016 to 0.025% by mass.

Additional research

Influence of non-metallic inclusions

Sulphides, formed at high sulphur content, form inclusions that: deteriorate the ductility of steel, reduce corrosion resistance, complicate cutting.

Graphical representation of the results shows a linear dependence of the deterioration of properties on the level of sulphur content.

Tables 1-3 present data on mechanical properties of the above steels at different sulphur content.

The impact toughness of 20GL steel decreases with increasing sulphur content due to the formation of brittle sulphide inclusions. This is especially critical at low temperatures, when impact toughness decreases by 3-4 times. Table 1 presents data on impact toughness of 20GL steel at different temperatures.

Table 1

Impact toughness of 20GL steel at different sulphur content*

Steel grade	KCU, MJ/m², at sulphur content, %			
	0,013	0,023	0,033	0,043
20GL	0,62 0,38	0,56 0,31	0,40 0,21	0,31 0,12

* Numerator - at test temperature +20°C, denominator - at -60°C.

As the sulphur content increases, a decrease in the tensile strength is observed, which makes the steel less resistant to mechanical loads. Table 2 shows the experimental strength data of 20GL steel.

Table 2

Strength of steel at different sulphur content

Steel grade	$a_в$, MPa, at sulphur content, %			
	0,013	0,023	0,033	0,043
20GL	650	635	610	605

Ductility is an important parameter affecting the technological properties of steel. Increased sulphur content leads to the formation of brittle grain boundaries, which reduces the relative elongation of steel, as shown in Table 3.

Table 3

Relative elongation of steels at different sulphur content

Steel grade	б, %, at sulphur content, %			
	0,013	0,023	0,033	0,043
20GL	21	20	15	10

Sulphur significantly reduces the fatigue strength of steel, as sulphide inclusions act as stress concentrations, which leads to crack initiation. According to studies, when the sulphur content increases above 0.025%, the fatigue strength of 20GL steel decreases by 1.5-2 times.

It was found that a sharp decrease in all properties of steels, especially toughness and ductility, is observed at sulphur content above 0.023%. For example, for most steels when increasing the sulphur content from 0.013% to 0.043%, impact toughness at normal test temperature decreases almost twofold, and at -60°C - more than three times. The graphs below show the dependence of mechanical properties of steel on sulphur content.

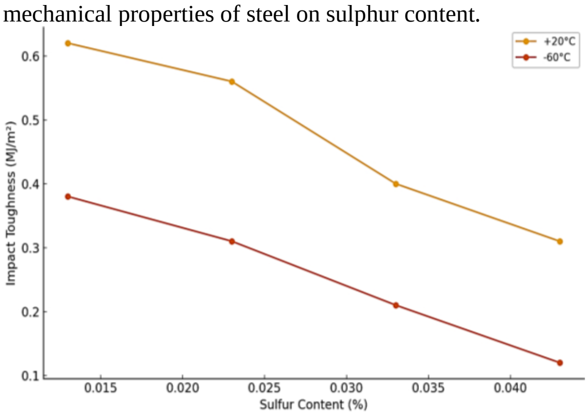

Fig. 4. Effect of sulphur content on impact toughness of steel at different temperatures

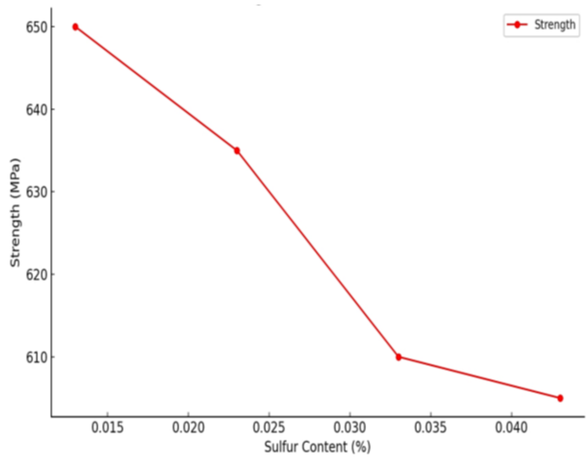

Fig. 5. Dependence of steel strength on sulphur content

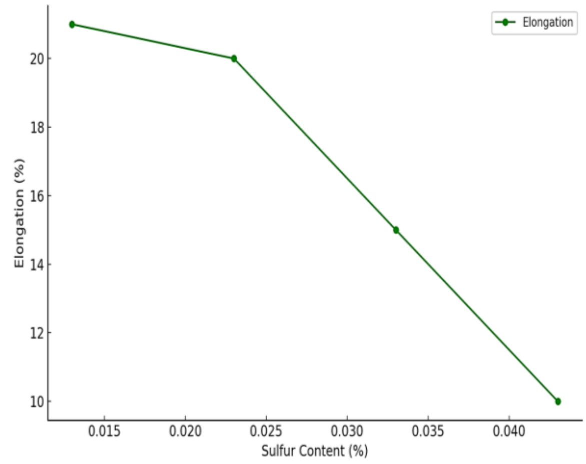

Fig. 6. Dependence of steel ductility on sulphur content

This effect is explained by the fact that sulfide and oxysulfide non-metallic inclusions are formed in the metal at the grain boundaries of the primary crystals, which weaken their bonding, which in turn leads to a decrease in the ductility and toughness of the cast metal. Thus, the higher the concentration of sulphur in the metal, the more non-metallic inclusions are present in the metal, resulting in lower mechanical properties such as impact toughness, strength and relative elongation.

4. Conclusion

The analysis of the conducted research has shown the necessity and expediency of developing technologies for refining steel melts in induction crucible furnaces (ICF) in order to achieve a stable reduction in sulphur concentration. This will allow to provide high quality characteristics of castings, especially in the conditions of production of critical parts for railway transport.

It is also required to make additional changes in steel casting melting technologies aimed at controlling and reducing the sulphur content in steels. The research results demonstrate that the increase of sulphur content in 20GL steel above 0.025% leads to a significant deterioration of mechanical properties. In particular:

The impact strength (KCU) decreases by a factor of 3 at -60°C, making the steel more brittle in low temperature applications.

The strength of the steel decreases by an average of 8%, which reduces its ability to withstand mechanical loads.

The ductility of the steel (relative elongation) is reduced by 50%, increasing the risk of failure under dynamic loads.

Fatigue strength decreases by 1.5-2 times, which is especially critical for parts operating under cyclic loads.

The obtained data confirm the necessity of strict control of sulphur content in foundry steels. The optimum sulphur level for 20GL steel is 0.015-0.025%, which provides high mechanical properties such as strength, impact toughness and ductility.

To achieve these indicators, it is recommended to implement modern desulphurisation methods, including:

Use of synthetic slags with high lime content.

The use of deoxidising agents (calcium, magnesium) to bind sulphur into stable compounds.

Treatment of steel outside the furnace (e.g. in furnace-ladle units or using vacuum treatment).

These measures will not only improve the performance characteristics of castings, but also increase their durability and reliability under conditions of intensive use.

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