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RESEARCH PAPER

The modifier effect on the structure and properties of 40CrNi3MoV steel

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ABSTRACT

This study presents the results of an investigation into the effects of a multifunctional modifier on the properties of 40CrNi3MoV structural steel. The modifier employed belongs to the INSTEEL class and comprises a complex combination of Ca, Ba, Ti, Nb and rare earth metals (REMs). The ingot modifier was pre-crushed to a 30-100 µm powder state. The synthesized modifier was encapsulated in aluminum foil and introduced into the furnace with the charge materials. Mechanical testing of the resulting steel samples included evaluation of tensile strength, hardness, elongation at fracture, impact toughness and wear resistance. The experimental results demonstrated that the applied modification did not lead to significant alterations in the steel's elemental composition, which remained within the standard specification limits. Modification resulted in a marked enhancement of the steel's hardness, strength and wear resistance. The ease of introducing the modifier into the melt, along with its minimal required dosage, makes the proposed method highly practical. These factors, combined with the observed strengthening effects, support its consideration as a broadly applicable approach for enhancing the mechanical properties of heat-treatable steels.

Keywords: complex modifier, powder, strength, hardness, wear resistance, structure.

INTRODUCTION

The study of modifiers and their influence on steel properties represents one of the most promising trends in contemporary physical metallurgy. This study direction has gained momentum due to the fact that conventional methods for enhancing steel performance, such as alloying, heat treatment and ingot modification, have largely reached their practical limits. It is noteworthy that current studies in this area predominantly focus on high-alloy steels, including heat-resistant, oxidation-resistant and corrosion-resistant grades. This choice appears to be fully justified. The cost of alloying modifiers is relatively high, which significantly increases the overall production cost of the final product. Furthermore, the process of introducing modifiers into liquid steel presents a considerable technological challenge. It requires the implementation of an additional processing stage, thereby complicating the production workflow [1–5].
In studies [6–10], refractory compounds such as Zr, TiN, Y_2O_3, AlTi, among others, have been employed as modifiers. These works investigate their influence on the properties of heat-resistant alloys. The findings demonstrate that the introduction of such modifiers has a beneficial effect on both strength and impact toughness. Moreover, significant improvements were also observed in critical functional properties, including long-term strength and creep resistance.
Studies [11–13] focus on the effect of modifiers on wear resistance. As modifying agents, researchers utilized structured composite materials and chemical compounds such as SiC, TiO_2, and others. Across all referenced investigations, the application of these compositions led to an improvement in wear resistance, with increases ranging from 5% to 20%.
An extensive review of the literature on the influence of modification on the properties of steels has led to the following conclusions:
- modification significantly alters the steel structure during primary solidification by increasing its dispersion;
- application of modifiers enhances both the mechanical properties and selected functional properties of steel;
- as modifiers, refractory compounds, primarily TiN, Y_2O_3, TiC, AlTi, and similar materials, are predominantly used. However, their high cost contributes to an increase in the overall production cost of the final product;
- the majority of investigations focus on high-alloy steels, particularly heat-resistant and corrosion-resistant grades.

Studies examining the effects of modification on the properties of medium-alloy steels are significantly less numerous. This is largely due to the comparatively lower mechanical performance of these steels and their use in less critical applications. However, it is important to note that medium-alloy steels, particularly those in the class of heat-treatable grades, constitute a substantial proportion of the steels consumed in the mechanical engineering sector.
According to widely accepted terminology, medium-alloy steels are defined as steels containing between 2.5% and 10% alloying elements. The term of complex-alloyed steels is more specific. This class includes steels that contain multiple alloying elements with differing effects on the size and stability of the α- and γ-phase regions, as well as varying tendencies toward carbide formation.
Thus, despite the considerable body of research dedicated to the modification of steels as a method for enhancing their properties, numerous open questions remain. These are primarily related to the characteristics of modifiers and the structural and phase transformations that occur upon their introduction.
It is important to emphasize that modification, as a means of influencing steel properties, differs fundamentally from alloying in its underlying mechanism of action. In alloying, similar to conventional alloying, the process involves alterations in the chemical composition of the steel. This leads to the formation of new phases and is typically accompanied by both phase and structural transformations.
In contrast, modification aims to improve steel properties predominantly through structural refinement, without inducing significant phase transformations.
It should be noted that the authors have previously conducted a series of studies focused on the introduction of complex modifiers and their effects on the properties of carbon steel [14]. Positive results were reported when powders of refractory oxides and pure metals were used.
The objective of this study is to investigate the effect of modifiers on the structure and properties of complex-alloyed steel. The selected material for this study is steel grade 40CrNi3MoV (Table 1).
Steel grade 40CrNi3MoV is classified as a complex-alloyed steel due to the presence of alloying elements of different natures. This steel is widely used in manufacturing facilities across the Republic of Kazakhstan as a structural material for components in mining and metallurgical equipment operating under complex and high-stress conditions.

The widespread application of this steel is attributed to its unique combination of high strength and toughness properties, making it particularly well-suited for demanding industrial environments.
This steel belongs to the class of heat-treatable chromium-nickel-molybdenum steels and is considered one of the most advanced grades among structural steels used in mechanical engineering. Owing to its nickel content, the steel exhibits a high reserve of toughness. The presence of molybdenum significantly reduces the tendency toward temper embrittlement, a phenomenon commonly observed in steels of this class. A key advantage of chromium-nickel-molybdenum steels lies in their excellent hardenability. Martensite and lower bainite structures can be reliably achieved throughout cross-sections up to 80–100 mm in thickness following full oil quenching. This combination of properties makes the steel highly suitable for the production of large-scale components where both high strength and toughness are critical performance requirements.

Table 1 Chemical composition of 40CrNi3MoV steel (SS 4543-2016)

Basic element content, %					Mechanical properties		
C	Mn	Cr	Ni	Other elements	σ_B, MPa	δ, %	KCU, J/cm^2
0.33-0.40	0.3-0.8	1.2-1.5	3.0-3.5	0.35-0.45 Mo 0.1-0.18	880	≥ 10	≥ 59

Nevertheless, the potential for further enhancement of the properties of steels in this class is nearly exhausted. This steel is alloyed with a small amount of vanadium, which contributes to grain refinement and provides a moderate improvement in strength compared to the 40CrNi2Mo grade. However, it is important to note that additional vanadium alloying necessitates an increased nickel content to maintain adequate toughness. Given the scarcity of nickel, this approach is considered undesirable. In this context, the application of modification-based treatments presents a promising alternative for improving steel properties, offering a more efficient route than further compositional adjustments.
As a modifier, a complex additive of the INSTEEL type was selected. It contains calcium (Ca), barium (Ba), titanium (Ti), niobium (Nb), and rare earth metals (REMs). A distinguishing feature of this modifier is its multi-component composition, which includes both alkaline earth metals and rare earth elements, as well as a strong carbide-forming element. This modifier is characterized by a crystalline structure, which is formed by rapid solidification from the molten state of the complex alloy.
The presence of calcium and barium elements with low vapor pressure results in slower interactions with the steel melt. This enhances the removal of sulfur and phosphorus and promotes the formation of non-metallic inclusions. The inclusion of rare earth metals (REMs) contributes to the formation of fine, stable hydrides, which contribute to an increase in corrosion resistance and reduces temper embrittlement. Titanium and niobium facilitate the formation of stable carbides, thereby increasing the steel's strength, hardness and wear resistance. Thus, the use of this complex modifier enables refinement of the steel's structure and improvement of its performance characteristics, without altering the base chemical composition.
It should be noted that the INSTEEL complex modifier is typically supplied in the form of chips or in fractionated form, and is conventionally used in this state for classical steel modification processes. In this study, however, the INSTEEL modifier is employed in the form of a powder. This form is expected to enhance its efficiency as a nucleation site activator during solidification, and potentially reduce the quantity required for effective modification.

MATERIAL AND METHODS

Fig. 1 shows the general appearance and phase composition of the INSTEEL class modifier used.

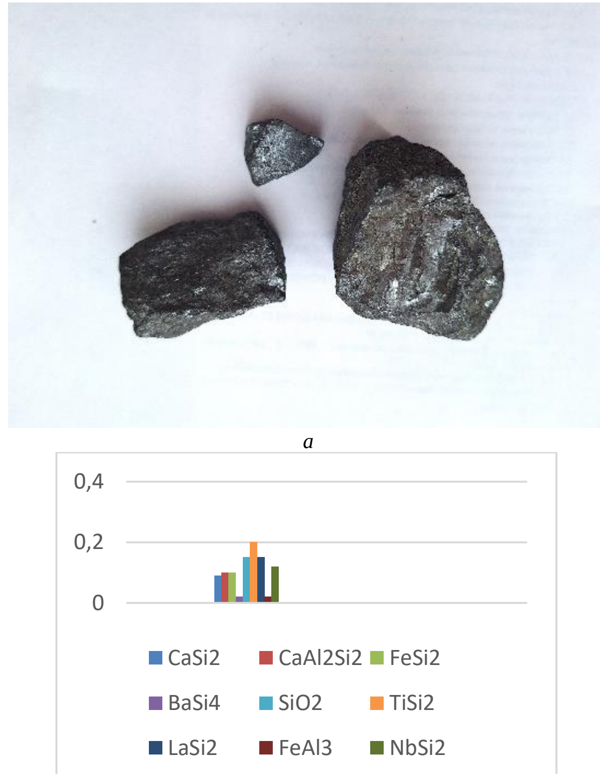


Fig. 1 General appearance (a) and phase composition (b) of the INSTEEL class modifier

The modifier was crushed and ground in an Emax ball mill for 40 minutes to achieve the required size. After grinding, its fractional composition was determined using an FSH-6K photosedimentograph. The results of the analysis are presented in **Table 2**.

Table 2 Fractional composition of the modifier after grinding

Fraction share, wr.%			
≥100 μm	100 – 60 μm	60-30 μm	≤30 μm
13	24	56	7

Steel grade 40CrNi3MoV was produced in a laboratory-scale induction furnace of the UIP-0.5 type. The charge materials included steel scrap, ferrochrome (FK005), ferronickel (FeNi50LC), ferromolybdenum (FMo60) and ferrovanadium (FeV40). The charge composition was calculated with consideration for the expected loss of alloying elements during melting. The modifier was added in an amount of 0.2 wt.% relative to the total charge mass. It was pre-packaged in aluminum foil and introduced directly into the charge. Upon melting of the aluminum foil, the modifier particles, having a lower temperature than the surrounding molten metal, acted as inoculating agents.
The melting process was carried out in an induction laboratory furnace equipped with an enhanced cooling system. A corundum-mullite crucible was used to prevent the carburization process. The molten metal was vigorously stirred under the influence of a magnetic field with an intensity of 100 A/cm for 3 min. The metal temperature before casting was 1560°C, measured using a submerged thermocouple (PPR type). The melt was poured into sand-clay molds, which replicated the shape of the samples for subsequent testing. After complete cooling, the samples underwent standard heat treatment: oil quenching at 850°C followed by tempering at 600°C in air.
Tensile tests were conducted at room temperature in accordance with SS 1497-84 using an INSTRON tensile testing machine equipped with an axial strain gauge. Impact toughness tests were performed at 20°C in accordance with SS 9454-78,

using a Zwick/Roell RKP 450 pendulum impact tester with a pendulum energy of 300 J.
The structure was studied using an Altami MET 5dik microscope; sections for the studies were prepared using Struers sample preparation equipment.
To determine the chemical and phase composition of the structure components, a SUPRA 55V PWDS scanning electron microscope with an X-ray analysis attachment was used.
The samples were tribologically tested on a Tribometer setup (CSM Instruments, Switzerland) under the following conditions: applied load 1 N; speed 5 cm/s; counter body a 3 mm diameter ball made of WC6; medium air; pre-treatment of samples, ultrasonic cleaning (USO) in isopropyl alcohol.
The reduced wear resistance was assessed based on the parameters of the wear scar on the sample using the following formula:

$$\varepsilon' = \frac{W}{A} \quad (1.)$$

where: W is the volume of wear products, mm^3;
A is the friction work, N*m.

The wear scar parameters, used to determine the volume of wear products, were measured using a WYKO NT1100 optical profilometer. The results of the tribological tests were automatically processed using the Instrum X Tribometer software.
The reduced wear of the sample was automatically calculated using Equation (1). Additionally, wear resistance was evaluated following the methodology described in references [15,16].

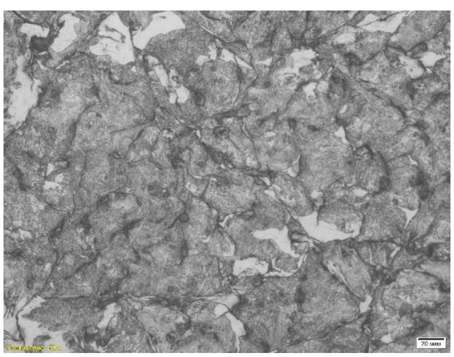
$$Ws = \frac{\Delta m}{\rho \cdot L \cdot F_N} \quad (2.)$$

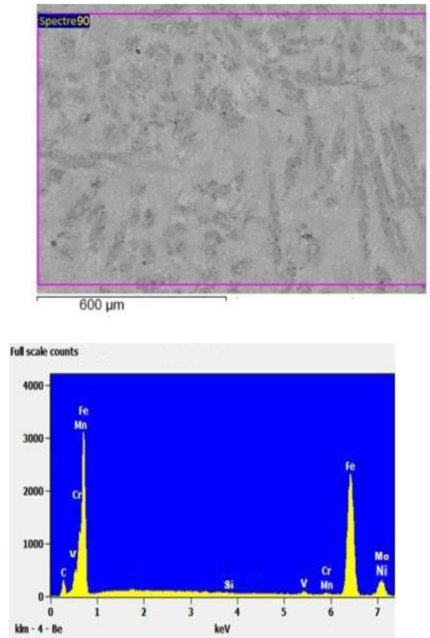
Table 3 Specific wear rate indicators

Sample	Sample 1	Sample 2
specific wear rate mm^2/H	2.19	1.57

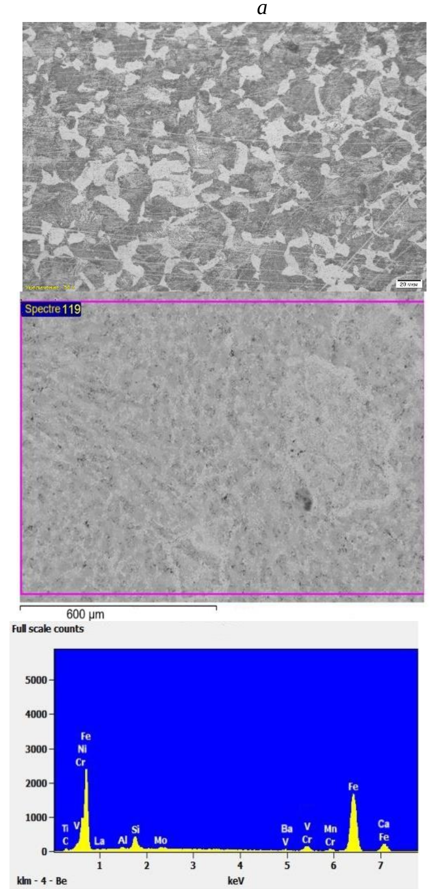
RESULTS AND DISCUSSION

Fig. 2 shows the structures of samples without introducing a modifier (sample 1) and after introducing a modifier (sample 2).





a



b

Fig. 2 The structure of 40CrNi3MoV steel: (a) Sample 1 - before modifier introduction; (b) Sample 2 after modification

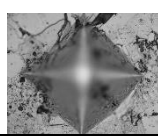
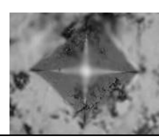
Table 4 presents the results of elemental total composition (spectra 90 and 119, **Fig. 2**).

Table 4 Sample elemental composition

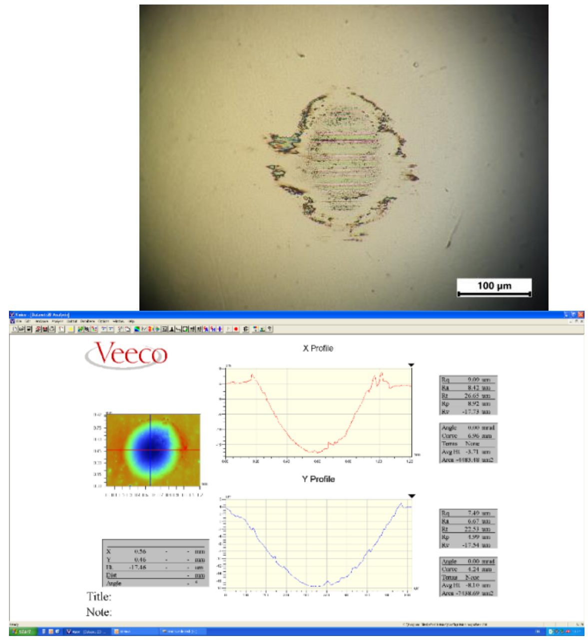
Spectrum	Spectre 90	Spectre 119
C	0.35	0.31
Si	1.3	1.2
Ti	0.03	0.15
Cr	1.36	1.40
Mn	0.35	0.43
Ca	-	0.68
Ba	-	0.35
Ni	3.68	3.63
Al	-	0.07
La	-	traces
Mo	0.38	0.37
Fe	rem	rem.

A comparison with the chemical composition of the initial sample (**Table 1**) confirms that the experimental samples meet the specification requirements for this steel grade. Although it was not possible to accurately quantify elements such as lanthanum (La), traces of its presence were detected in the structure.
The structural analysis reveals that, following the introduction of the modifier, sample 2 exhibits a more refined and homogeneous structure. Such structural modification is expected to result in improvements in fundamental mechanical properties, including hardness, strength and related characteristics.
Table 5 presents the mechanical property data obtained for the experimental sample. Steel grade 40CrNi3MoV without modification was used as the reference material.
As evidenced by the data in Table 5, all measured mechanical properties are higher in sample 1.
A comparison of the steel structures before and after modification at higher magnification reveals a finer and more uniform morphology of the sorbite colonies. This structural refinement is likely the key factor contributing to the enhanced mechanical performance observed in the modified steel relative to the unmodified baseline.

Table 5 Properties of 40CrNi3MoV steel after modification

Sample	Sample 1	Sample 2
Hardness, HV	272 	320 
σ_p, MPa	860	970
δ, %	11	10
Impact toughness , J/cm^2	62	58
Reduced wear of the sample, mm^3/ (N·m)	$4.56 \cdot 10^{-6}$	$3.45 \cdot 10^{-6}$

The observed increase in the dispersion of sorbite appears to be associated with an enhanced formation of nucleation sites as a result of modification. Refractory particles of rare-earth metals (REMs) and titanium act as additional nucleation sites. These particles inhibit excessive grain growth during solidification. During recrystallization, which occurs as a consequence of thermal treatment, the grain morphology exhibits a high degree of inheritance from the prior structure. This inherited grain structure contributes significantly to the refined dispersion of the steel structure following modification.
Wear resistance was also evaluated using the fabricated samples. The results presented in **Table 5** indicate a noticeable improvement in wear resistance following modification.
Fig. 3 shows the wear scars of the studied samples. A visual examination reveals that, in the modified steel sample, the wear scar is characterized by smoother edges and a more uniform crater depth. This observation suggests, firstly, an increase in surface hardness; and secondly, a more homogeneous distribution of structural components. The quantitative characteristics of the wear scars are summarized in the table.



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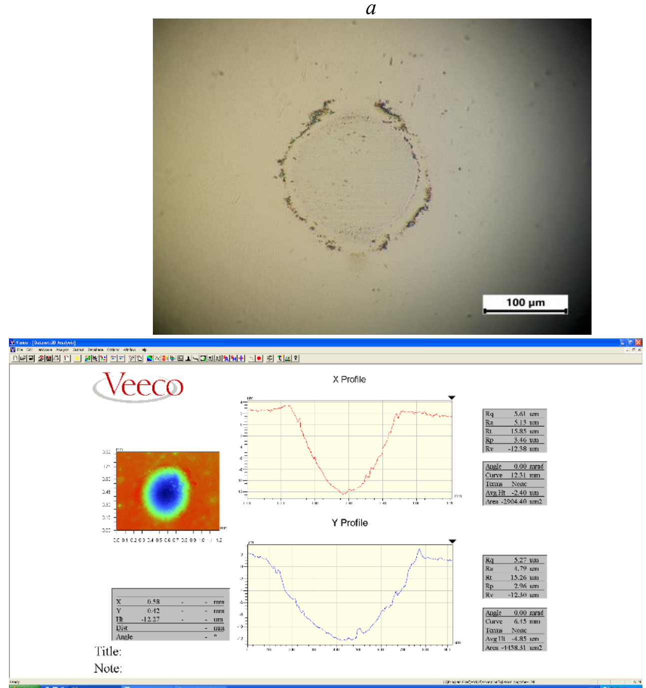

b

Fig. 3 Wear scar of 40CrNi3MoV steel before (*a*) and after (b) introducing a modifier, ×2500

Table 6 Characteristics of the experimental sample wear scars

Wear scar parameters	Sample 1		Sample 2	
	X-profile	Y-profile	X-profile	Y-profile
R_q, um	5.61	5.27	9.09	7.49
R_a, um	5.13	4.79	8.42	6.67
R_v, um	-12.38	-12.3	-17.73	-17.54

As shown by the data in **Table 6**, all wear parameters for sample 2 are significantly improved compared to sample 1. Both the diameter and depth of the wear scar are substantially reduced, in both the X- and Y-axis directions.

CONCLUSION

The results of this study demonstrate that the introduction of a complex modifier, comprising alkali and rare-earth metals (REMs), as well as titanium (Ti) and niobium (Nb) in the form of a powder with a particle size distribution of 100–30 µm, leads to substantial structural refinement. This structural refinement results in a notable enhancement of mechanical properties, including an average increase in hardness and wear resistance of approximately 25%. Simultaneously, a 12% improvement in strength is observed. However, this is accompanied by a moderate reduction in ductility and impact toughness. Despite the observed reduction in ductility and impact toughness, the experimental sample fully complies with the requirements of SS 4543-2016, including the specified elemental composition. The findings of this study indicate that modification using a complex INSTEEL-class modifier, introduced in the form of a powder with a particle size range of 30–100 µm, results in a significant enhancement of the performance characteristics of 40CrNi3MoV steel. The simplicity of the modifier's introduction, along with its low consumption, makes this approach a promising and versatile method for improving the strength properties of heat-treatable steels.

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