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Austenite Stability and Wear Resistance of High-Manganese Steels

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Purpose. Classification of wear-resistant components used in metallurgical equipment by category and optimization of high-manganese steel selection. **Design / Method / Approach**. The study was conducted on steels produced in induction furnaces with water quenching at 1050 °C. Samples of 5 × 3 × 3 mm³ were subjected to slow plastic deformation by compression. The degree of deformation was determined by the ratio of the sample thickness before and after deformation. The magnetic state was evaluated by the magnetometric method using a Faraday balance. **Findings**. At 20–30% deformation, 110Mn8 formed 2.787 vol.% α′-martensite, 110Mn10 – 0.263 vol.%, 110Mn13 – 0.107 vol.%, and 110Mn18 – 0.006 vol.%. Steels 110Mn8 and 110Mn10 exhibit low austenite stability, while 110Mn13 and 110Mn18 are metastable. A classification of parts by operating conditions was proposed: I – especially critical purpose (110Mn13, 110Mn18), II – critical purpose (110Mn10), III – general purpose (110Mn8). **Theoretical Implications**. The study enhances understanding of the role of martensitic transformation in the wear resistance of high-manganese steels and clarifies the relationship between chemical composition and austenite stability. **Practical Implications**. The classification enables optimized steel selection for parts based on operating conditions, reducing material costs and improving equipment reliability. **Originality / Value**. This is the first study to propose a classification of metallurgical equipment parts by categories, considering austenite stability, facilitating rational material selection. **Research Limitations / Future Research**. Future research should explore the effects of additional alloying elements and compare them with other deformation types. **Article Type**. Empirical.

Keywords:

high-manganese steel, austenite, martensitic transformation, wear resistance, Hadfield steel, metallurgical equipment, and impact wear, plastic deformation

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Мета. Класифікація зношуваних деталей металургійного обладнання за категоріями та оптимізації вибору високомарганцевих сталей. **Дизайн / Метод / Підхід**. Дослідження проводили на сталях, виготовлених в індукційних печах з гартуванням у воді з 1050 °C. Зразки розміром 5 × 3 × 3 мм³ піддавали повільній пластичній деформації стисненням. Ступінь деформації визначали за співвідношенням товщини зразка до і після деформації. Магнітний стан оцінювали магнітометричним методом за допомогою балансу Фарадея. **Результати**. Встановлено, що при деформації 20–30% у 110Mn8 формується 2,787 об.% α′-мартенситу, у 110Mn10 – 0,263 об.%, у 110Mn13 – 0,107 об.%, у 110Mn18 – 0,006 об.%. Сталі 110Mn8 і 110Mn10 мають низьку стабільність аустеніту, тоді як 110Mn13 і 110Mn18 є метастабільними. Запропоновано класифікацію деталей за умовами експлуатації: I – особливо критичного призначення, II – критичного призначення, III – загального призначення. **Теоретичне значення**. Дослідження розширює знання про вплив мартенситного перетворення на зносостійкість високомарганцевих сталей і уточнює зв’язок між хімічним складом та стабільністю аустеніту. **Практичне значення**. **Оригінальність / Цінність**. Класифікація дозволяє оптимізувати вибір сталі для деталей залежно від умов експлуатації, зменшуючи витрати на матеріали та підвищуючи надійність обладнання. **Обмеження дослідження / Майбутні дослідження**. Рекомендується дослідити вплив додаткових легуючих елементів та порівняти з іншими типами деформації. **Тип статті**. Емпірична.

Ключові слова:

високомарганцева сталь, аустеніт, мартенситне перетворення, зносостійкість, сталь Хейдфілда, металургійне обладнання, ударне зношування, пластична деформація

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In heavy machinery engineering, lining plates, hammers and crusher hammers, bottom, teeth and rockers of quarry excavator buckets, cones and bowls of large and medium crushing cone crushers, linings of ball and rod mills are made mainly out of Hadfield steel (110Mn13(casting) – Standard in Ukraine). One of the unique advantages of high-manganese steel is the high ability of manganese austenite to work hardening, which determines the hardness value of HB 500-600. The steel is also distinguished by high values of plastic characteristics (relative elongation δ and narrowing Ψ) from 15 to 40%, impact toughness KCU from 1.5 to 3.0 MJ/m^2 (Wen, 2014; Gürol, 2020). Moreover, these properties are preserved in the temperature range from -40 to 80 °C.

However, despite numerous studies (Sazhnev & Snizhno, 2023; Sereda et al, 2012; Sheyko et al, 2021) of the influence of various factors on the properties of high-manganese steel and extensive experience in its industrial use, the performance characteristics of castings from it remain very unstable. In some cases, they do not meet the requirements. Even the same type of castings from the same enterprise under the same operating conditions differ in service life by several times. This does not allow to ensure high reliability of equipment operation and indicates a reserve of quality of high-manganese casting.

The widespread opinion about the high wear resistance of 110Mn13(casting) steel regardless of the nature and operating conditions led to its use as a universal wear-resistant material. But high strengthening properties of 110Mn13(casting) steel can be obtained only under conditions of strong static or shock loading. At low loads, its ability to harden deteriorates.

In many literature sources, this behavior of manganese steels is explained by the initial microstructure and phase changes during the operation of products (Yan et al, 2023; Ayadi et al., 2024; Ding et al., 2022; Li et al, 2023). In the work (Han et al., 2023), where the tribological behavior of Hadfield steel under sliding wear conditions was studied, it was found that increasing the load leads to the formation of a nanocrystalline layer with martensitic transformation. Martensitic transformation provides additional strengthening and, thus, reduces abrasive wear. The degree of stability of austenite is a key factor in martensitic transformation and is related to its morphology, grain size, carbon and manganese content, neighboring phase and orientation.

International standards define a fairly wide range of concentration limits for carbon and manganese content. This leads to the fact that in production, in matters of specific content, they are guided more by their own experience than by the limits recommended by the standard.

Experience in application and scientific research of the properties and operating conditions of parts made of high-manganese steel have produced a number of proposals for the content of carbon, manganese and other elements for specific operating conditions. Thus, in conditions of predominantly abrasive wear, the recommended content of carbon is >1.3%, manganese <12%, phosphorus up to 0.12%. Under predominantly shock loads, the recommended content of carbon is <1.3%, manganese >12%, phosphorus <0.08% (Snizhnoi et al, 2024; Sheyko et al, 2023).

Such recommendations for the composition of high-manganese steels are aimed primarily at managing the stability of austenite and obtaining a certain phase-structural composition (Sheyko, 2023; Sheyko, 2016) for specific operating conditions. At the same time, martensitic transformation is one of the key factors affecting the wear resistance of steel during operation (Ol'shanetskii et al., 2016; Bhattacharya et al., 2024).

The variability in the performance of high-manganese steel castings is a critical issue that necessitates a deeper understanding of the material's behavior under diverse operational conditions. The instability of austenite and its propensity for martensitic transformation are influenced not only by chemical composition but also by processing parameters such as heat treatment and casting techniques (Sheyko et al, 2023). For instance, improper heat treatment can lead to the formation of undesirable phases, such as carbides, which compromise the steel's toughness and wear resistance (Sereda et al, 2012). Furthermore, the cooling rate during casting affects the grain size and distribution of austenite, which in turn impacts the material's ability to undergo work hardening (Ding, 2022). These factors highlight the need for precise control over manufacturing processes to achieve consistent material properties.

Research has also shown that the tribological performance of Hadfield steel is highly dependent on the type of wear mechanism encountered. In abrasive wear scenarios, the formation of a hardened surface layer through work hardening is crucial for extending service life (Hu, & Fu, 2024). However, under low-load or sliding wear conditions, the absence of sufficient stress to induce martensitic transformation results in suboptimal performance (Ayadi et al., 2024). This underscores the importance of matching the material's composition and microstructure to the specific wear conditions it will encounter. For example, in applications involving high-impact loads, a higher manganese content is preferred to enhance austenite stability and promote martensitic transformation under dynamic loading (Snizhnoi et al, 2024).

Another critical aspect is the role of alloying elements beyond carbon and manganese. Elements such as chromium, molybdenum, and phosphorus can significantly influence the phase stability and mechanical properties of high-manganese steel (Li et al, 2023). For instance, controlled additions of chromium can enhance corrosion resistance and stabilize austenite, while excessive phosphorus can lead to embrittlement (Sheyko et al, 2023). These findings suggest that a tailored alloying strategy, combined with optimized processing, is essential for maximizing the performance of Hadfield steel in specific applications.

To address the challenges associated with the inconsistent performance of high-manganese steel, this study aims to classify wear parts used in metallurgical production based on their operational roles, such as abrasive or impact-dominated environments. By categorizing these components, it becomes possible to recommend specific compositional and processing guidelines for each category (Sheyko et al, 2021). Additionally, the research focuses on investigating the stability of austenite during plastic deformation, with a particular emphasis on the conditions that trigger martensitic transformation. Understanding these mechanisms is vital for developing strategies to enhance the wear resistance and reliability of high-manganese steel components (Bhattacharya et al., 2024).

Ultimately, this work seeks to bridge the gap between theoretical insights and practical applications by providing a framework for optimizing the composition, microstructure, and processing of Hadfield steel. By addressing the variability in performance and tailoring the material to specific operating conditions, it is possible to improve the durability and efficiency of heavy machinery components, thereby enhancing the overall reliability of metallurgical equipment (Yan et al, 2023).

The purpose of this work: to classify wear parts of equipment for metallurgical production by category depending on their purpose; to research the stability of austenite to martensitic transformation during plastic deformation.

Hadfield steel, in particular grade 110Mn13 and its variants (110Mn8, 110Mn10, 110Mn18), is a key material for the manufacture of wear-resistant parts for metallurgical equipment such as cone crushers, ball mills and buckets for mining excavators. Its exceptional ability to be hardened due to its austenite stability and tendency to martensitize makes it particularly suitable for withstanding the intense impact wear typical of these applications. Impact wear, which occurs due to dynamic loads during crushing and grinding, is the primary failure mechanism for such parts, requiring a deeper understanding of the impact of compositional variations in Godfield steel on its performance.

Materials and Methods

The experimental steels were melted in induction crucible electric furnaces by the fusion method, ingots 100x100x200 mm were poured, which were quenched in water from 1050 °C (holding time 3 hours). From the middle of the quenched ingots, samples in the form of rectangular parallelepipeds measuring 5x3x3 mm^3 were cut out by cold mechanical means. Slow plastic uniaxial compression deformation at room temperature was carried out on a special laboratory installation. The degree of residual deformation $D=(d_0-d)/d_o$ was calculated from the ratio of the thicknesses before (d_0) and after (d) deformation. The magnetic state of the samples (paramagnetic austenite and ferromagnetic α′-martensite deformation) after each act of compression was determined by the magnetometric method (Faraday balance) (Snizhnoi et al, 2012). In the case of the $\gamma \rightarrow \alpha'$ transformation, the amount of $P_{\alpha'}$ formed ferromagnetic α′-

martensite deformation was determined using a method similar to (Snizhnoi, 2011). This method allowed us to determine an ultra-low amount of ferrophase in volume percentages (from 0.001%), since it takes into account the influence of the magnetic moment of the paramagnetic austenite matrix. The chemical composition of the experimental manganese steel melts is given in Table 1.

To ensure the accuracy and reproducibility of the experimental results, the preparation of the steel samples followed a standardized protocol. The induction crucible electric furnaces used for melting were calibrated to maintain consistent temperatures and minimize impurities during the fusion process. The ingots were cast under controlled conditions to avoid defects such as porosity or inclusions, which could affect the mechanical properties of the samples. The quenching process at 1050 °C was carefully monitored to achieve a uniform austenitic microstructure, as this initial structure is critical for the subsequent deformation and phase transformation studies (Sheyko et al, 2023). The holding time of 3 hours was selected to ensure complete dissolution of carbides and homogenization of the alloying elements within the austenite matrix (Sereda et al, 2012).

Table 1 – Chemical composition of the researched steels (mas., %) (Created by the authors)

No.	Type of steel	C	Mn	Si	Cr	Al	P	S	Ni	Mo
1	110Mn8 (casting)	1,14	8,60	0,66	0,10	0,019	0,088	0,040	–	–
2	110Mn10 (casting)	1,19	10,47	0,45	0,01	0,022	0,100	0,015	–	–
3	110Mn13 (casting)	1,16	13,80	0,76	0,10	0,018	0,092	0,016	–	–
4	110Mn18 (casting)	1,23	17,50	0,62	1,37	–	0,030	–	0,35	0,24

The selection of the sample dimensions (5x3x3 mm³) was based on the requirements of the magnetometric analysis and the deformation setup, ensuring that the samples were small enough to allow precise measurements while maintaining structural integrity during compression. Cold mechanical cutting was employed to avoid introducing thermal stresses or microstructural changes that could arise from hot cutting methods (Ding et al., 2022). The uniaxial compression tests were conducted at a controlled strain rate to simulate slow plastic deformation, which is representative of certain operational conditions in heavy machinery components (Tressia & Sinatora, 2023). The laboratory installation was equipped with high-precision sensors to measure the thickness of the samples before and after deformation, enabling accurate calculation of the residual deformation degree.

The magnetometric method using the Faraday balance was chosen for its high sensitivity in detecting the formation of ferromagnetic α′-martensite within the paramagnetic austenite matrix. This method is particularly effective for quantifying ultra-low amounts of martensite, which is essential for studying the early stages of the γ→α′ transformation (Snizhnoi, 2011). The calibration of the Faraday balance was performed prior to each measurement to account for environmental magnetic fields and ensure reliable data. The influence of the paramagnetic austenite matrix on the magnetic moment was carefully considered, as described in (Snizhnoi et al, 2012), to isolate the contribution of the ferromagnetic phase. This approach allowed for precise determination of the volume percentage of α′-martensite, even at levels as low as 0.001%.

To complement the magnetometric analysis, the chemical compositions of the experimental steels (Table 1) were verified using spectroscopic methods to ensure compliance with the specified alloying ranges. The variations in manganese content (8.60–17.50%) and carbon content (1.14–1.23%) across the four steel types were intentionally designed to investigate their effects on austenite stability and martensitic transformation under deformation (Sheyko et al, 2023). Additional alloying elements, such as silicon, chromium, aluminum, phosphorus, sulfur, nickel, and molybdenum, were included to study their influence on the mechanical and tribological properties of the steels, particularly in relation to wear resistance under different loading conditions (Li et al, 2023). The absence of certain elements in some steel types (e.g., nickel and molybdenum in steels 1–3) was deliberate to isolate the effects of manganese and carbon.

The experimental design also accounted for potential variations in microstructure due to differences in cooling rates during quenching. To mitigate this, all samples were quenched in water under identical conditions, and the middle section of the ingots was used to ensure uniformity in microstructure and avoid surface-related anomalies (Yan et al, 2023). The data collected from the deformation and magnetometric analyses were statistically processed to identify trends in the relationship between chemical composition, deformation degree, and martensitic transformation, providing a robust basis for classifying wear parts and optimizing their performance in metallurgical applications (Bhattacharya, 2024).

Results and Discussion

Analysis of operating conditions of replaceable parts of metallurgical production equipment

Working parts of heavy machinery (plates, cones, bowls, hammers, side walls of crusher working areas, main structural elements of mill drums, parts of quarry excavator buckets, etc.) used at metallurgical enterprises are made entirely or lined with plates of 110Mn13 (casting) steel.

During operation, these parts come into contact with the material being crushed, therefore they are subjected to tensile, compressive, bending, and shear loads. In this case, a combination of two or more types of destructive action on the same part is possible, and purely abrasive wear without additional loads is also possible. All of these parts, during normal operation, without the occurrence of emergency situations, fail due to abrasive wear, while the thickness of the worn steel layer can reach 100-150 mm or more (Fig. 1).

Thus, during trouble-free operation, replaceable parts of almost all types of equipment made of 110Mn13 (casting) steel, despite the fact that the static and dynamic loads acting on them differ significantly, fail due to abrasive wear, and premature failure due to the occurrence of a crack or other reasons is the result of abnormal situations during operation or poor-quality casting.

Depending on the degree of static or dynamic load under conditions of abrasive wear and the possibility of abnormal situations during operation, replaceable parts are proposed to be divided into three categories (Table 2).

For parts of II group and, especially, III group, it is possible to use steels with a reduced manganese content compared to 110Mn13 (casting) steel. The physical and mechanical properties of such steels are lower, but they are sufficient to ensure reliable operation of parts subjected to minor static or dynamic loads during operation (Hrechanyi et al., 2024; Belodedenko et al., 2022; Belodedenko et al.; Belodedenko et al., 2024; Yavtushenko et al, 2019).

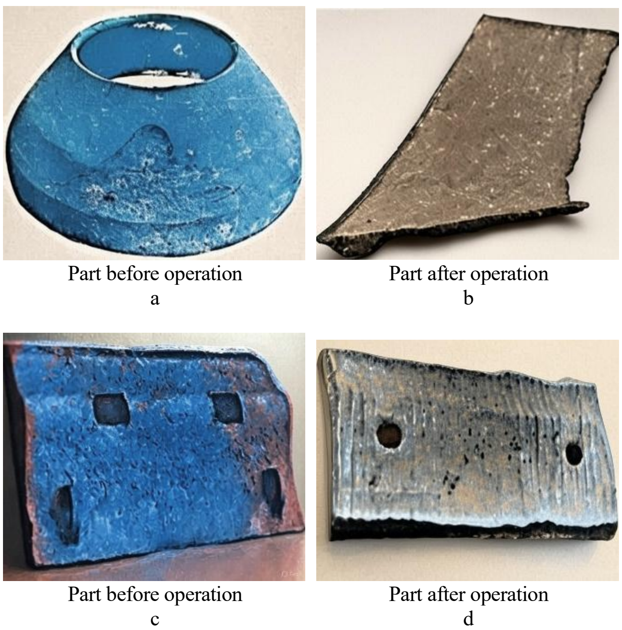
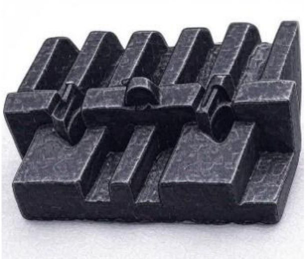


Figure 1 – Parts of crushing and grinding equipment and quarry excavators made of 110Mn13(casting) steel: a, b – cone crusher armor; c, d – single-shaft ball mill lining (Created by the authors)



Part before operation
e

Part after operation
f

Part before operation
g

Part after operation
h

Figure 1 (continued) – Parts of crushing and grinding equipment and quarry excavators made of 110Mn13(casting) steel: e, f – unified ball mill lining; g, h – front wall of excavator bucket with teeth (Created by the authors)

Table 2 – Distribution of replaceable wear parts of equipment for metallurgical production by categories depending on operating conditions (Created by the authors)

Number of the category	Name of the category	Type of steel	Name of the part
I	Especially critical purpose	110Mn13 (casting), 110Mn18 (casting)	Armor of coarse crushers; teeth and front walls of excavator buckets; hammer crusher blades.
II	Critical purpose	110Mn10 (casting)	Armor of jaw and cone crushers for medium and fine crushing; conveyors; parts of mills that crush solids with a diameter of more than 100 mm.
III	General purpose	110Mn8 (casting)	Details of ball and rod mills that grind solids with a diameter of up to 100 mm.

The reason for the decrease in the physical and mechanical properties of high-manganese steels with a reduced manganese content is primarily lower austenite stability. However, as shown by the results of research (Sazhnev & Snizhnoi, 2023), in some cases, the decrease in austenite stability becomes a positive factor for increasing the wear resistance of steel due to the increase in the microhardness of the surface layer of unstable austenite steels.

The increase in hardening and wear resistance of steels is explained by the appearance of martensitic phases under the influence of plastic deformation. To study the process of the appearance of deformation martensite, the following magnetometric studies were carried out.

Stability of austenite of manganese steels to martensitic transformation under the action of plastic deformation

For the research, steels with variable manganese content and the content of all other main components of the chemical composition at the average level of the standard for 110Mn13(casting) steel were used. In 110Mn8(casting) and 110Mn10(casting) steels an austenitic structure with a small amount of residual carbides is observed, and in 110Mn13(casting) and 110Mn18(casting) steels only the austenitic phase is observed. This is fully consistent with the works (Wen, 2014; Gürol, 2020; Sazhnev, 2023; Snizhnoi, 2024).

Fig. 2 shows the dependence of the amount of formed α′-martensite in the studied steels on the relative degree D of plastic deformation by compression. The amount of formed α′-martensite deformation in 110Mn13(casting) and 110Mn18(casting) steels from the degree of deformation is significantly less than in 110Mn8(casting) and 110Mn10(casting) steels. For example, for D≈30% in 110Mn8(casting) steel α′-martensite is formed in the amount of 2.787 vol.%, in 110Mn10(casting) steel – 0.263 vol.%, in 110Mn13(casting) steel – 0.107 vol.%, in steel 110Mn18(casting) – 0.006 vol.%. It should be noted that the deformation level of 20-30% is quite real in the surface layer of the cone of a large crushing crusher.

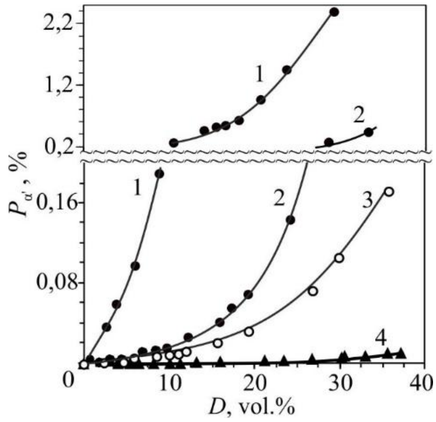


Figure 2 – Dependence of the amount of $P_{\alpha'}$ of the resulting α′-martensite on the degree of deformation D in the studied steels:1 – 110Mn8(casting), 2 – 110Mn10(casting), 3 – 110Mn13(casting), 4 – 110Mn18(casting) (Created by the authors)

Based on the capabilities of magnetometric equipment (the ability to measure ferrophase from 0.001 vol.%), the values of relative plastic deformation D were obtained, at which the first portions of deformation forming α′-martensite were recorded for each steel grade, which are given in Table 3.

Table 3 – The magnitude of deformation D at which the first portions of $P_{\alpha'}$ forming α′-martensite deformation in the studied steels were recorded (Created by the authors)

№	Type of steel	D, %	$P_{\alpha'}$, vol.%
1	110Mn8(casting)	0,66	0,004
2	110Mn10(casting)	0,85	0,003
3	110Mn13(casting)	6,03	0,007
4	110Mn18(casting)	13,05	0,003

The difference in the amount of martensite occurring deformation in steels can be explained by the different level of stability of austenite to the phase transformation γ→α′. As we can see, 110Mn18(casting) steel is the most stable, at the degree of plastic deformation D=37.15% the austenite structure is mainly preserved, and the amount of forming α′-martensite is $P_{\alpha'} \approx 0{,}011$ vol.%. 110Mn8(casting) steel, on the contrary, is the most unstable, at the degree of plastic deformation D=29.19% the amount of forming α′-martensite is $P_{\alpha'} \approx 2.787$ vol.%. That is, in the austenite matrix during deformation, α′-martensite rapidly accumulates. Table 4 offers a classification of the stability of austenite to martensitic transformation in manganese steels.

Table 4 – Classification of austenitic manganese steels stability (Created by the authors)

№	Type of steel	D, %	$P_{\alpha'}$, vol.%
1	110Mn8(casting)	0,66	0,004
2	110Mn10(casting)	0,85	0,003
3	110Mn13(casting)	6,03	0,007
4	110Mn18(casting)	13,05	0,003

The formation and accumulation of new phases directly affects the physical, mechanical and service properties of steel. Therefore, the issue of controlling phase stability and changes in properties during operation (deformation is one of the main factors) is very relevant.

Influence of Martensitic Transformation on Wear Resistance

The observed differences in the formation of α′-martensite across the studied steels have significant implications for their wear resistance under operational conditions. The rapid accumulation of martensite in 110Mn8(casting) steel, due to its lower austenite stability, contributes to a pronounced increase in surface hardness during deformation (Sazhnev, 2023). This hardening effect is particularly beneficial in applications involving moderate to low dynamic loads, where the formation of a martensitic surface layer enhances resistance to abrasive wear (Kozłowska et al, 2023). For instance, the high-volume fraction of α′-martensite (2.787 vol.% at D=29.19%) in 110Mn8(casting) steel suggests that it is well-suited for components in Category III (general purpose), such as ball and rod mill linings, where abrasive wear dominates but impact loads are minimal (Hrechanyi, 2024).

Conversely, the high stability of austenite in 110Mn18(casting) steel, which results in minimal martensite formation (0.011 vol.% at D=37.15%), makes it ideal for Category I (especially critical purpose) components, such as coarse crusher armor and excavator bucket teeth, which experience severe impact and abrasive wear (Snizhnoi et al, 2024). The stable austenite structure in this steel allows it to maintain its toughness and resist crack propagation under high dynamic loads, which is critical for preventing premature failure in demanding applications (Sheyko et al, 2023). The intermediate behavior of 110Mn10(casting) and 110Mn13(casting) steels positions them as suitable for Category II (critical purpose) components, such as jaw and cone crusher armor, where a balance between hardness and toughness is required (Belodedenko et al., 2023).

The relationship between manganese content and austenite stability is further elucidated by the microstructural analysis. The presence of residual carbides in 110Mn8(casting) and 110Mn10(casting) steels indicates incomplete dissolution during heat treatment, which may reduce austenite stability and promote martensitic transformation under deformation (Sereda et al, 2012). In contrast, the fully austenitic structure of 110Mn13(casting) and 110Mn18(casting) steels, achieved through higher manganese content, enhances phase stability and delays the onset of martensitic transformation (Wen et al, 2014). This microstructural difference explains the observed trends in Table 3, where lower manganese steels exhibit martensite formation at significantly lower deformation levels (D=0.66% for 110Mn8(casting) vs. D=13.05% for 110Mn18(casting)).

The study of martensitic transformation in Hadfield steels (110Mn8, 110Mn10, 110Mn13, 110Mn18) revealed their different suitability for metallurgical equipment subject to impact wear. In particular, 110Mn8 steel, due to its low austenite stability and rapid formation of α′-martensite (2.787 vol% at 29.19% strain), provides significant surface hardening, which is beneficial for metallurgical mill parts subject to abrasive wear with moderate impact loads. On the other hand, 110Mn18 steel, with its high austenite stability (0.011 vol% martensite at 37.15% strain), is ideal for components such as coarse crusher armor or excavator bucket teeth that are subject to significant impact wear. These results emphasize the importance of adapting Hadfield steel grades to the operating conditions of metallurgical equipment.

Optimization of Steel Composition for Specific Applications

The classification of wear parts into three categories (Table 2) provides a practical framework for selecting the appropriate steel grade based on operational conditions. The use of 110Mn8(casting) and 110Mn10(casting) steels for less demanding applications (Categories II and III) not only ensures adequate performance but also offers cost savings due to their lower manganese content (Yavtushenko, 2019). However, the trade-off in mechanical properties, particularly reduced toughness, must be carefully considered to avoid premature failure under unexpected dynamic loads (Belodedenko et al., 2022). For Category I components, the superior toughness and phase stability of 110Mn13(casting) and 110Mn18(casting) steels justify their use despite higher material costs (Sheyko et al, 2023).

The magnetometric data (Table 3 and Fig. 2) also highlight the importance of controlling deformation levels to optimize martensitic transformation. For instance, in applications where surface hardening is desired, operating conditions should be designed to induce deformation levels that trigger martensite formation without compromising the bulk properties of the steel (Tressia & Sinatora, 2023). This can be achieved through careful design of equipment components to ensure that the surface experiences sufficient compressive or shear stresses during operation (Ding et al., 2022). Conversely, for components requiring high toughness, such as excavator bucket teeth, the use of 110Mn18(casting) steel with minimal martensite formation ensures resistance to crack initiation under high-impact loads (Snizhnoi, 2024).

Implications for Manufacturing and Quality Control

The variability in martensite formation and its impact on wear resistance underscores the need for stringent quality control during the manufacturing of high-manganese steel components. Factors such as heat treatment parameters, cooling rates, and alloying precision significantly influence the initial microstructure and, consequently, the stability of austenite (Sereda et al, 2012). For example, improper quenching can lead to the formation of undesirable phases, such as carbides or retained austenite, which reduce the steel's ability to undergo work hardening (Sheyko et al, 2023). To address this, manufacturers should adopt standardized heat treatment protocols tailored to the specific steel grade and application, ensuring a fully austenitic microstructure for high-manganese steels like 110Mn18(casting) (Yan et al, 2023).

Furthermore, the wide range of manganese content permitted by international standards contributes to variability in performance, as manufacturers often rely on empirical practices rather than optimized compositions (Li et al, 2023). The results of this study suggest that precise control over manganese content, as well as other alloying elements like carbon and phosphorus, is essential for achieving consistent wear resistance and mechanical properties (Sheyko et al, 2023). For instance, the recommended carbon content of >1.3% for abrasive wear conditions and <1.3% for shock-loaded conditions (Snizhnoi et al, 2024) should be strictly adhered to during alloy design to ensure optimal austenite stability and martensitic transformation behavior.

This study demonstrated that the stability of austenite against martensitic transformation in high-manganese steels is directly influenced by manganese content, significantly affecting their wear resistance. Specifically, steel 110Mn8 (8.6% Mn) exhibits the lowest austenite stability, forming 2.787 vol.% α′-martensite at 29.19% deformation, which enhances surface hardness and is suitable for abrasive wear under low loads (Category III, general purpose). Conversely, steel 110Mn18 (17.5% Mn) shows high austenite stability, producing only 0.011 vol.% martensite at 37.15% deformation, making it optimal for high-impact loads (Category I, especially critical purpose). Steels 110Mn10 and 110Mn13 occupy an intermediate position and are recommended for critical applications (Category II). For clarity, austenite is the crystalline structure of steel that provides ductility and work-hardening capacity, while martensitic transformation refers to the process by which austenite transforms into a harder martensite phase under deformation. The investigated steel grades—110Mn8, 110Mn10, 110Mn13, and 110Mn18 (casting)—were selected to analyze their performance under abrasive and impact wear conditions, enabling the development of recommendations for their use in metallurgical equipment.

Future Research Directions

The findings of this study open several avenues for future research. First, the role of minor alloying elements, such as chromium, nickel, and molybdenum, in modulating austenite stability and wear resistance warrants further investigation, particularly for 110Mn18(casting) steel, which contains these elements (Table 1) (Li et al, 2023). Second, the effect of deformation rate on martensitic transformation should be explored, as dynamic loading conditions in real-world applications may differ from the slow uniaxial compression used in this study (Jabłońska et al, 2022). Finally, the development of predictive models that correlate chemical composition, microstructure, and operational conditions with wear performance could enable more precise material selection and component design, reducing the variability observed in high-manganese steel castings (Bhattacharya et al, 2024).

Limitations of the Study

Despite the results demonstrating the dependence of austenite stability and wear resistance of high-manganese steels (110Mn8, 110Mn10, 110Mn13, 110Mn18) on their chemical composition and deformation conditions, this study has certain limitations that must be considered when interpreting and applying its findings.

Firstly, the experiments were conducted at room temperature, which does not capture the full range of temperature conditions encountered in the operation of metallurgical equipment. It is known that high-manganese steels, such as Hadfield steel, retain their plastic properties in the temperature range from -40 to 80 °C (Wen, 2014); however, the influence of elevated or reduced temperatures on martensitic transformation and wear resistance was not evaluated in this study. This limitation may affect the applicability of the results to conditions where components experience significant temperature fluctuations, such as in hot grinding mills.

Secondly, although the study covered four steel grades with varying manganese content (8.6–17.5%), the analysis was limited to the specific chemical compositions listed in Table 1. The influence of other alloying elements, such as chromium, molybdenum, or nickel, present in 110Mn18, was only partially investigated, and their contribution to austenite stability and wear resistance requires further exploration. Additionally, the carbon content in the studied steels varied within a narrow range (1.14–1.23%), which does not fully allow for the evaluation of recommendations regarding carbon content (>1.3% for abrasive wear and <1.3% for impact loads) proposed in the literature (Snizhnoi et al., 2024).

Thirdly, the deformation tests were performed under slow plastic compression conditions, which do not fully replicate the dynamic or cyclic loading experienced in real operational conditions of metallurgical equipment, such as impact wear in crushers. The deformation rate may influence the kinetics of martensitic transformation, and this limitation should be considered when extrapolating the results to high-speed or impulsive loading scenarios.

Finally, the laboratory samples, sized 5x3x3 mm³, used in the magnetometric analysis do not reflect the scale and geometry of real components, such as crusher armor or mill linings, where the worn layer thickness can reach 100–150 mm. Scaling laboratory data to industrial components may be challenging due to differences in stress distribution, microstructural homogeneity, and cooling conditions during casting.

These limitations highlight the need for further research, particularly investigating the effects of temperature, a broader range of chemical compositions, varying deformation rates, and simulations of real operational conditions. Such studies will refine recommendations for optimizing high-manganese steels for specific applications in metallurgical equipment.

Conclusions

The comprehensive investigation into the performance of high-manganese Hadfield steel (110Mn13 casting) and its variants (110Mn8, 110Mn10, and 110Mn18 casting) in heavy machinery components for metallurgical production has provided valuable insights into their wear resistance, phase stability, and suitability for specific operational conditions. The study successfully classified replaceable wear parts into three categories – especially critical, critical, and general purpose – based on the degree of static and dynamic loads and the dominant wear mechanisms. This classification enables the targeted selection of steel grades, with 110Mn13 and 110Mn18 recommended for high-impact applications (Category I), 110Mn10 for balanced performance under moderate loads (Category II), and 110Mn8 for low-load abrasive wear scenarios (Category III).

The analysis of operating conditions revealed that abrasive wear is the primary failure mechanism for components made of high-manganese steel, with worn layer thicknesses reaching 100–150 mm under normal operation. Premature failures due to cracks or casting defects were attributed to abnormal operational conditions or poor manufacturing quality, highlighting the need for stringent quality control during production. The magnetometric studies demonstrated a clear correlation between manganese content and austenite stability, with 110Mn8 exhibiting the least stable austenite (forming 2.787 vol.% α′-martensite at D=29.19%) and 110Mn18 the most stable (0.011 vol.% at D=37.15%). This variation in martensitic transformation directly influences surface hardening and wear resistance, with less stable austenite promoting hardness in low-load conditions and stable austenite ensuring toughness in high-impact environments.

The findings underscore the importance of tailoring steel composition and microstructure to specific operational requirements. For abrasive wear, higher carbon (>1.3%) and lower manganese (<12%) contents are optimal, while shock-loaded conditions benefit from lower carbon (<1.3%) and higher manganese (>12%). The presence of minor alloying elements, such as chromium and molybdenum in 110Mn18, further enhances phase stability and corrosion resistance, warranting their consideration in alloy design (Li, 2023). Manufacturing processes, particularly heat treatment and quenching, were identified as critical factors affecting microstructural uniformity and phase stability, necessitating standardized protocols to minimize variability in performance.

The study also highlighted the potential for cost optimization by using lower-manganese steels (110Mn8 and 110Mn10) in less demanding applications, provided that mechanical properties are carefully balanced to prevent failure under unexpected loads. The magnetometric method proved highly effective for quantifying ultra-low martensite fractions (from 0.001 vol.%), offering a robust tool for studying phase transformations and guiding material optimization.

Future research should focus on the role of minor alloying elements, the influence of deformation rates on martensitic transformation, and the development of predictive models to correlate composition, microstructure, and wear performance. By implementing these findings, manufacturers can enhance the reliability, durability, and cost-effectiveness of high-manganese steel components, ultimately improving the operational efficiency of metallurgical equipment.

The study confirms that Hadfield steel, in particular grades 110Mn8, 110Mn10, 110Mn13 and 110Mn18, is the optimal material for wear-resistant parts of metallurgical equipment such as crushers, mills and excavator buckets due to its unique ability to carburize and martensitize. The data obtained allow us to adapt the composition and microstructure of these steels to the operating conditions, in particular to impact wear, which is the main failure factor in applications with high dynamic loads. The classification of parts into categories depending on operating conditions and recommendations for the selection of steel grades help to improve the reliability and durability of metallurgical equipment subject to abrasive and impact wear.

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