Reports in Mechanical Engineering
Vol. 6, No. 1, 2025, pp. 225-235
ISSN: 2683-5894, DOI: https://doi.org/10.31181/rme557

Design and Performance Evaluation of Dual Interchangeable Carbide Inserts for Wheelset Reprofiling

Arslan Shakhanov[1], Asanhan Shakhanov[1*], Nurlan Kudaibergenov[2], Ainash Bolatova[2*], Kyrmyzy Balabekova[2*], Ramona Blanes[3]
[1]Saken Seifullin Kazakh Agrotechnical University, Astana, 010000, Republic of Kazakhstan
[2]L.N. Gumilyov Eurasian National University, Astana, 010000, Republic of Kazakhstan
[3]University of Glasgow, UK

Article Info

Article history:

Received August 15, 2025
Revised October 25, 2025
Accepted November 18, 2025

Keywords:

Dual Interchangeable Carbide Inserts (DICI),
Wheelset Machining,
Hardness,
Surface Roughness,
Cutting Parameters

ABSTRACT

The rising cost of carbide tools, which can account for up to 20% of manufacturing expenses, necessitates the development of cost-effective machining solutions. This study investigates the performance of dual interchangeable carbide inserts (DICI) applied in wheelset reprofiling. The research focuses on the relationship between cutting parameters (cutting speed, feed rate, and cutting depth) and surface quality indicators, including hardness and surface roughness. A dfigual interchangeable carbide inserts (DICI) configuration mounted on a specially designed tool holder is proposed to improve tool performance and durability. Experimental results demonstrate that using DICI increases surface hardness by up to 12% compared to conventional inserts while maintaining acceptable surface roughness. Microstructural analysis confirms the formation of compressive stresses and reveals a correlation between cutting regimes and thermal effects in the surface layer. The proposed approach improves machining efficiency, enhances tool life, and provides a cost-effective solution for wheelset maintenance in railway engineering.

Corresponding Author:
Asanhan Shakhanov
Saken Seifullin Kazakh Agrotechnical University, Astana, 010000, Republic of Kazakhstan
Email: a.shakhanov@kazatu.edu.kz
Ainash Bolatova
L.N. Gumilyov Eurasian National University, Astana, 010000, Republic of Kazakhstan
Email: bolatova_ab_1@enu.kz
Kyrmyzy Balabekova
L.N. Gumilyov Eurasian National University, Astana, 010000, Republic of Kazakhstan
Email: balabekova_kg@enu.kz

1. Introduction

Modern manufacturing increasingly relies on advanced machining technologies to improve productivity and reduce production costs. In railway engineering, wheelset maintenance is a critical and economically significant task, particularly in Kazakhstan, where the cost of new wheelsets remains high.

As a result, wheelset reprofiling has become a widely adopted solution due to its economic efficiency. The reuse of wheelset materials with preserved physical and mechanical properties significantly reduces operational costs and improves resource utilization (Bellavista et al., 2021; Li, 2024).

However, machining wheelsets from St2T steel poses significant challenges, primarily due to rapid tool wear and unstable cutting conditions. Premature degradation of carbide inserts leads to poor surface quality, increased surface roughness, and variations in hardness, ultimately increasing production costs.

During machining, surface defects such as cracks and irregularities frequently occur, complicating the cutting process and often resulting in sudden tool failure. As shown in Figure 1, surface defects are the primary cause of insert failure during wheelset machining (Ameen, 2024; Wang & Feng, 2007).

Conventional single-carbide inserts are not always capable of maintaining stability under such conditions, thereby reducing tool life and machining efficiency (Maksimov et al., 2025).

To address these limitations, this study proposes the use of dual interchangeable carbide inserts (DICI), which improve load distribution, enhance cutting stability, and increase tool durability.

Figure 1: Surface Defects on Wheelsets Leading to Carbide Insert Failure.

To address this issue, the authors conducted a series of studies to develop a machining method based on the pairing (doubling) of carbide inserts. An analysis of international research and machining techniques, revealed that various methods are employed to process 2T-grade steel, the primary material used in wheelsets. Among these, the method involving paired carbide inserts proved to be the most effective and technically feasible.

2. Materials and Methods

The objective of this study is to ensure the maximum operational performance of replaceable carbide cutting inserts in the machining of wheelsets by creating conditions enabled through additional fastening mechanisms.

Scientific novelty lies in:

- Establishing the relationship between cutting parameters and surface quality metrics during the machining of wheelsets using replaceable carbide inserts.

Numerous researchers (Wang & Feng, 2009; Wang & Wang, 2011; Zhao et al., 2021) have addressed the doubling of cutting tools, particularly with respect to thermal ranges determined by peak temperatures. For instance, Zhao et al. (Zhao et al., 2012) focused on enhancing the operational performance of replaceable carbide inserts by investigating the temperature-dependent variation in their electromagnetic properties. Other notable contributions include:

- Wang and Feng (Wang & Feng, 2009), who improved the performance characteristics of turning tools equipped with ceramic inserts for precision machining of heat-resistant alloys by incorporating graphene and spark plasma sintering technology.
- Zhao et al (Zhao et al., 2021), who optimized the geometry of assembled broaches to enhance high-speed broaching processes.
- Wang and Wang (Wang & Wang, 2011), who significantly advanced cutting performance by employing complex surface modification techniques – such as electron-beam alloying and the application of wear-resistant coatings on carbide tools.

Carbide tools are highly valued in modern manufacturing for their exceptional hardness and wear resistance compared to other tool materials (Dewangan et al., 2019). However, the high cost of new carbide tools and their rapid degradation under demanding operating conditions necessitate frequent, costly replacements. The main challenge lies in the sudden onset of tool failure, which negatively affects cutting performance and insert longevity (Kalavathi & Bhuyan, 2018).

Studies in this field have yielded mixed results, often influenced by the specific composition of the workpiece material and the initial wear state of the tools. Furthermore, the economic and practical viability of paired insert configurations remains a subject of ongoing debate within the engineering community.

In this study, dual interchangeable inserts are defined as two closely aligned carbide inserts mounted on a common holder using a threaded fastening system, as shown in Figure 2. The proposed paired insert assembly replaces a single large insert on the machine tool.

Figure 2: The Proposed Experimental Dual Interchangeable Carbide Insert

3. Methodological Approach

The methodological approach combines experimental investigation and statistical analysis to evaluate the performance of dual interchangeable carbide inserts (DICI).

The cutting process was analyzed considering the following parameters:

spindle speed (n, rpm),
feed rate (s, mm/rev),
cutting depth (t, mm).

These parameters define the machining regime and directly influence surface integrity characteristics such as hardness (HB) and surface roughness (Rz).

A second-order experimental design (Box–Behnken) was applied to determine the relationship between cutting parameters and response variables. Experimental data were processed using Statistica 10 software and validated under industrial conditions.

The methodological approach combines experimental testing of the hardness of machined parts with performance evaluation under standard conditions. While most researchers focus on chip-breaking processes, the wear resistance of carbide inserts remains insufficiently studied, often resulting in a one-sided understanding of tool failure mechanisms (kumar Naik & Maity, 2018; Senthilkumar et al., 2014).

To address this gap, a comprehensive strategy is proposed for selecting cutting parameters – such as cutting depth, feed rate, and cutting speed – whose combinations define the machining regimes. This methodology enables the evaluation of surface hardness characteristics across different alloys and material combinations.

The simultaneous pairing of two or more inserts is influenced by high temperatures and pressures. Previous studies have examined the microhardness of deformed zones in carbide inserts. Research by Alnejaili et al. (Alnejaili et al., 2015), convincingly demonstrated that more rigid cutting regimes can improve the mechanical and operational properties of re-machined components (Senthilkumar et al., 2014).

The authors' preliminary investigations aim to identify optimal methods for assessing the reliability of carbide inserts, particularly in machining wheelsets, where high tool wear is common. The proposed methodological framework combines experimental validation with theoretical analysis of tool wear resistance. Testing is being conducted to evaluate the performance and durability of inserts under standard operating conditions.

Mechanically clamped carbide inserts, when in contact with the workpiece surface, demonstrate similar technological characteristics—such as microhardness and residual stresses—to monolithic inserts. Based on data collected under industrial conditions, it was established that up to 80% of parts machined on CNC equipment are produced using reduced cutting regimes. These conservative settings are primarily used to ensure consistent tool life and maintain surface quality and dimensional accuracy. However, poor machinability of heat-resistant materials and suboptimal parameter selection often result in unnecessarily low cutting regimes, ultimately reducing productivity.

A joint analysis of primary wear types and failure modes in replaceable carbide inserts revealed that up to 40% of tool failures during material processing are due to breakage. Chipping and fracturing are also widespread failure mechanisms. In fact, tool failures due to chipping and edge breakage account for approximately 70% to 75% of all insert failures in assembled tools.

4. Degree of Scientific Development.

Despite the broad investigation into cutting tool performance in terms of strength and durability, the specific issues of maximizing the performance and quality of replaceable carbide inserts through additional clamping and analysis of dependencies on cutting regimes and temperature remain underexplored—both in Kazakhstan's mechanical engineering sector and globally. These aspects remain insufficiently studied with respect to surface integrity and cutting reliability.

To date, the functional performance of cutting tools has been explored from various angles, including tool strength and wear resistance. G.S. Andreev, B.S. Balakshin, A.I. Betaneli, V.F. Bobrov, V.F. Bezyazychny, S.M. Bratan, B.M. Brzhozovsky, S.A. Vasin, and Vereshchaka have made significant contributions to the field of metal cutting and tooling science.

5. Practical Implementation.

The practical realisation of the proposed concept relies on reproducing and managing the cutting forces acting on the workpiece surface, as well as on manufacturing the dual-interchangeable carbide insert (DICI). This requires the expertise of highly skilled toolmakers and designers, which is readily available at most manufacturing enterprises. Direct replication of the DICI form and insert-holder geometry during cutting is feasible; however, alternative geometries are necessary to ensure high cutting efficiency and enable the optimal selection of cutting regimes for wheel re-profiling.

When studying the condition of carbide inserts, the following structural zones can be distinguished: defective and decarburized layers; defect-free surface layers; layers strengthened by additional treatment; internal residual stresses of varying signs originating during sintering; and alloyed surface layers (Kalavathi & Bhuyan, 2018; kumar Naik & Maity, 2018; Sherov et al., 2022).

One of the primary causes of insert cracking is the rapid cooling of the insert surface upon exiting the cutting zone due to contact with coolant. This contact can lower surface temperature by 30–40%, significantly reducing the service life of the paired inserts.

Figure 3. Disassembled Configuration of Dual Carbide Inserts Showing Thermo-Mechanical Effects on the Workpiece Surface

Cutting tools often fail to meet the required service life for various reasons, including tool breakage. The absence of interchangeable inserts selection may lead to diverse changes in the economic evaluation criteria of the surface layer: increased stresses due to grinding modes, formation of microcrack networks caused by rapid heating and cooling, and the appearance of chipping on the cutting edge (SHARIF et al., 2007). Each of these factors implies increased costs as their frequency grows, ultimately resulting in economically inefficient and irrational methods of tool restoration.

For instance, the use of low-quality, inexpensive inserts may allow tool operation to be maintained (without catastrophic failure), and regrinding can significantly extend tool life by improving durability through higher sharpening quality compared to new inserts, along with an additional period of wear resistance. This process necessitates a short-term increase in tool consumption (during the accumulation of worn inserts for regrinding), the replacement of inserts in the tool holder upon reaching a certain wear threshold, and other deviations from established routines. However, the main drawback of low-quality inserts is an increase in the number of tool adjustments and an overall decline in productivity over the research period.

Peer-reviewed. Thus, the authors theoretically justify the pairing of carbide inserts on a holder, with mechanical replacement via size matching, as a potentially economically viable solution to address sudden defects in wheelsets.

The simultaneous pairing of two or more inserts is associated with exposure to high temperatures and pressure, which favorably influences heat dissipation from the surface.

In the literature, significant contributions have been made by Ye Min So, who investigated the cutting properties of carbide tools through complex surface modification via electron-beam alloying and the application of wear-resistant coatings.

Several studies have examined the microhardness of the deformed zone in carbide inserts, including work by Alnejaili et al., (Alnejaili et al., 2015) which convincingly demonstrates that more rigid pairing and cutting regimes improve the mechanical and operational properties of re-ground parts.

To determine the hardness of the machined surface after paired cutting, experimental methods were employed, including an experimental design in the computer program Statistica 10 and the information software MP2/P30.

The analysis and study of the obtained results are based on the scientific principles of cutting theories, manufacturing technologies, and materials science (Senthilkumar et al., 2014; SHARIF et al., 2007; Sherov et al., 2022).

Figure 3 illustrates the equipment and instruments used in the experimental study of paired cutting of St 2-T steel wheelsets.

a) b) c)

d) e) f)

Figure 4: Equipment and Instruments Used in the Experimental Study

a – RAFAMET UCB-125 CNC Machine; b – Disassembled Insert in the Holder (view from both Sides); c – Tool for Measuring the Diameter of Wheelsets; d – Electronic Device for Hardness Measurement; e – Hardness Measurement of the Wheelset Surface with a Notch; f – Surface Compression Measurement.

6. Discussion

The authors conducted experimental studies on the determination of hardness using mechanically fastened dual-carbide inserts at the Akmola Wagon-Building Plant.

In the study (Li, 2024), experimental investigations of the cutting process for steel 2T with dual carbide inserts were conducted under various cutting conditions using the specified materials. Ultimately, the economic feasibility of the implementation was evaluated. A planning matrix and experimental results based on a central composite design of the second order for three factors were presented, consisting of a full factorial experiment of the 2^3 type.

Table 1: Experimental Design Matrix and Results

Planning: Initial Stage,	Three-Factor Box-Behnken Design			320-360 HB
	Spindle Speed, n (rpm)	2 ÷11 Feed Rate, s (mm/min)	0,5÷5 Cutting Depth, t (mm)	
1	9	2	0,5	290
2	11	3	1	311
3	13	4	1,5	315
4	18	5	2	355
5	27	6	2,5	360
6	29	7	3	370
7	9	8	3,5	341
8	11	9	4	330
9	13	10	4,5	330
10	18	11	5	340
11	27	12	0,5	350
12	29	13	1	360
13	9	14	1,5	370
14	11	15	2	350
15	13	16	2,5	340
16	18	17	3	350

The results of the experimental studies demonstrated that optimal hardness determination enables the achievement of high-quality indicators for the machined surfaces, as shown in Table 1.

The experimental design allowed comparison of response surfaces, presented as 3D graphs of the dependencies HB = f(t, n) and Ra = f(t, n) (Figure 4). Figure 5 illustrates the hardness response surface as a function of cutting depth and spindle speed (rpm values were selected based on the technical specifications of the RAFAMET UCB-125 machine).

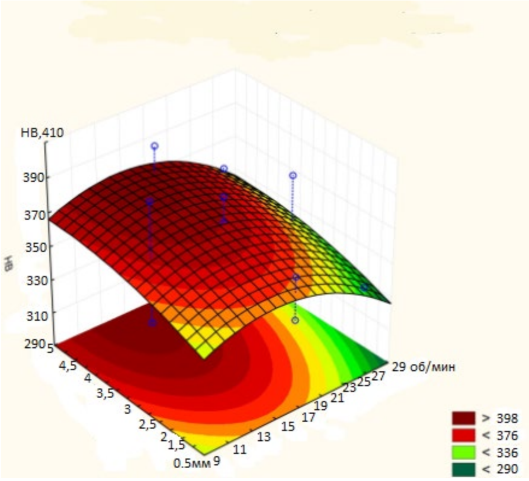


Figure 5: Response Surface Showing the Dependence of Hardness (HB) on Cutting Depth (t) and Spindle Speed (n)

The objects of the experimental study included the RAFAMET UCB-125 machine, wheelsets of rolling stock made from steel grade St 2T, as well as mechanically fastened dual tangential carbide inserts KS-35 and tangential inserts LNUX 301 940 SN-DM Pramet. The equipment and sensors used for hardness and surface roughness measurements were also involved.

Thus, an increase in cutting depth leads to an increase in hardness. The diagram shows that at cutting depths of

0.5-5 mm and spindle speeds of 9-29 rpm, the optimal hardness is approximately 360 HB (Figure 3). At a cutting depth of 2.5 mm, the optimal hardness reaches 370 HB, while a decrease in cutting depth results in a corresponding decrease in hardness. At a spindle speed of 18 rpm, the most optimal hardness value is 355 HB. Both decreasing and increasing the spindle speed beyond 27 rpm reduce hardness (see Figure 6).

Additionally, predicted value profiles and desirability functions were generated using the Statistica software (Figure 4). From the diagrams, the necessary optimal cutting parameter values can be identified. For example, to achieve a hardness of 360 HB, the following cutting conditions should be applied: spindle speed (n) = 27 rpm, cutting depth (t) = 2.5 mm, and feed rate (s) = 6 mm/min.

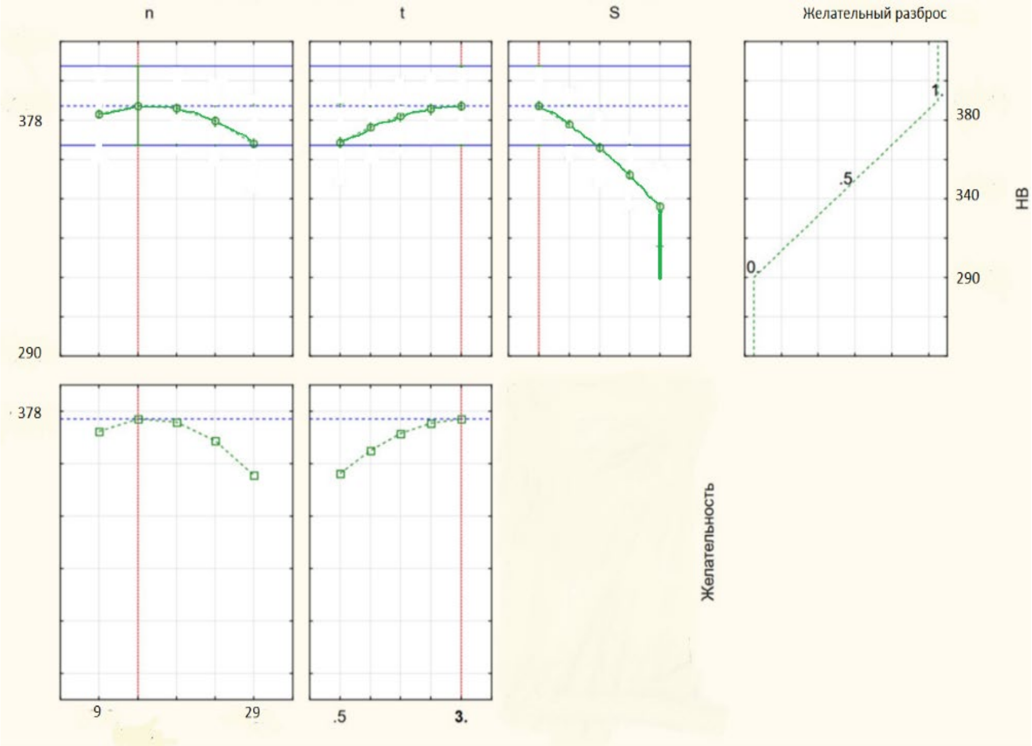


Figure 6: Predicted Value Profiles and Desirability Functions for the Hardness of Wheelset Surfaces.


a) b)

Figure 7: a) Surface roughness of the Wheelset After Machining; b) Surface roughness of the Wheelset Before Machining.

:

The data from Table 1 were incorporated into a database and recorded for further processing to obtain optimal values.

Cutting parameters were calculated using one of three methods in each case:

- Analytical (calculated) — using formulas based on the machine's technical specifications.
- Software-based — employing specialized software MP2/P30L. This method determines cutting parameters for modern CNC lathes, such as the RAFA MET UCB-125, using the same formulas but computed by the machine, thereby minimising the likelihood of errors.
- Tabular — selection of cutting parameters based on personal experience and reference tables; this method is typically used in conjunction with the analytical approach.

Table 2 presents the feed rate and cutting depth values affecting surface roughness.

Table 2: Dependence of Feed Rate, Cutting Depth, and Surface Roughness. Workpiece Material: St. 2T, σ = 750 MPa, Rm = 300 MPa

Feed Rate, mm/rev	0,5÷5	R_z
	t, mm	Surface Roughness
2x	0,5	75
3	1	77
4	1,5	78
5	2	79
6	2,5	80
7	3	81
8	3,5	82
9	4	82
10	4,5	83
11	5	83

As can be seen from the data in Table 2, the surface roughness significantly increased at a cutting depth of t=2.5 mm and reached the required roughness value of R=80 μm. The working characteristics were evaluated during tests under standard cutting conditions depending on the quality of the machined surface, represented by the RzR_zRz parameter.

The results of the experimental study on the influence of cutting parameters on the hardness of the machined surface during double-layer cutting show that, by selecting cutting modes, surface hardness can be controlled. It is known that steel grade St 2 has a guaranteed hardness range of 290–390 HB. The hardness variation does not exceed 100 HB according to SSAB technical requirements. The graphs show that the initial hardness of St 2 steel does not decrease (see Figs. 6a and 6 b). If an increase in the initial hardness is required, it can be achieved at cutting parameters of n=27 rpm, t=2.5 mm, and s=6 mm/rev (see Fig. 6a, b, curve 5).

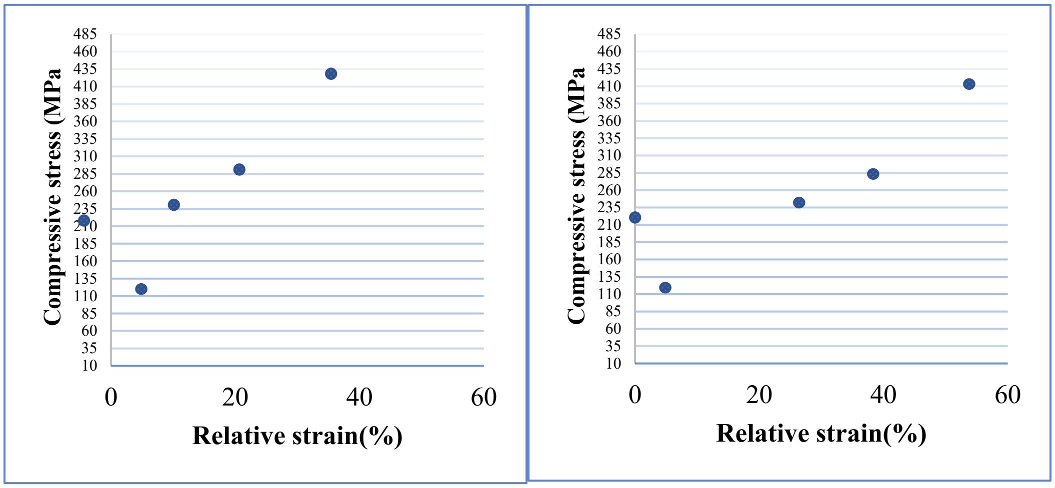
It was found that increasing cutting depth (ttt) and feed rate (sss) increases the hardness (HB) of the machined surface (see Fig. 6a, b). Optimal cutting parameters were determined as n=13 rpm, t=2.5 mm, and s=6 mm/rev.

A microstructural analysis of compressive stresses (SEM/EBSD under hard-turning conditions) was conducted to determine the effects of operating modes on surface hardening and the causes of defect formation. The sample and cross-sectional area used for analysis are shown in Figure 1. The analysis showed changes in the wheel pair's hardness with cutting depth in the range of 0.5 to 5 mm.

For microstructural analysis of steel grade St 2T, an MET-3 electron microscope was used, along with the MP2/P30L software for digitization and operational control. Electron microscopes, including scanning (SEM) and transmission (TEM), allowed investigation of the structure at magnifications up to 200,000× and higher, as well as the identification of defect sizes and their causes.

The results of direct measurements of sample dimensions and strains, and of the calculated stress intensity, are presented in stress-strain diagrams obtained during the experiment. A stress-strain curve based on computer calculations from relative deformations of the wheel pair microstructure was also plotted. The microstructure of the tested sample confirms these results.

As can be seen from the obtained diagrams, the stress-strain relationships exhibit almost coinciding curves. The yield strength of steel St 2T reaches 750 MPa during initial operation but decreases significantly afterward. During compression tests, the steel's ultimate strength did not return to its initial value.



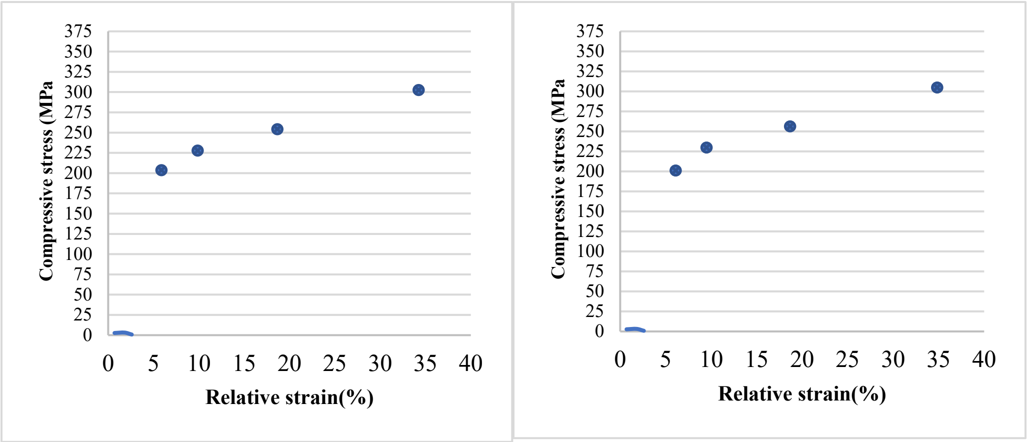
a) b)

Figure 8: Stress-Strain Dependency Diagrams: a – Curve Based on Experimental Data; b – Curve Obtained from Microstructure Analysis

Table 3: Results of Direct Measurements of Wheelset Surface Dimensions, Strains, and Calculated Stress Intensity

Degree of Sample Deformation, %	Compression Force, F (kH)	Cross-sectional Area of the Specimen A, cm²	Specimen Diameter h, mm	Stress σ, MPa
13	188.9095	0.6674	921.3	189.4 /178
19,7	212.638	0.6691	923.3	244.7/227?4
25,3	257.0974	0.6733	929.6	306.8/298
31,7	318.550	0.6752.s	931,7	449.0/431

According to the data presented in Table 3 and Figure 8, (a) shows the stress-strain diagram based on experimental measurements, while (b) displays the curve obtained from computer analysis of relative strains in the microstructural image. As seen in Table 3, the strain degree of the wheelset ranged from 13% to 31.7%, indicating that in approximately one out of every three cases, defects are present, primarily due to violations in casting technology. With an increase in sample diameter from 9 to 21 mm, a simultaneous increase in stress to 449 MPa was observed. From the diagrams, the stress-strain dependencies show nearly coinciding curves; the yield strength of steel grade 2 reaches 235 MPa. During compression tests, the metal did not reach its initial ultimate strength. Tensile tests were not performed because the full-size sample fractured. Figure 9 presents the microstructure of the tested wheelset sample.



a) b)

Figure 9: Stress-Strain Diagrams: a – Curve Based on Experimental Data; b – Curve Obtained from Microstructure Analysis.

Values of stress intensity arising in the surface layer of the processed sample (Table 3).

According to the data obtained in Table 3, the stress-strain diagrams were constructed (Fig. 8, a) from direct measurements of deformations during testing. Fig. 8, b shows the stress-strain diagrams obtained by computer calculations during the analysis of the microstructural image.

Stress-strain diagrams: a - curve according to the experimental data; b - curve obtained by analyzing the microstructure showed. that an increase in stress during continuous operation of the wheelset at a relatively low deformation of more than 10 per cent reaches a sharp peak of up to 220 MPa, after which the growth occurs smoothly. When regrinding the surface, the stress on the wheelset axis decreases; for example, for a diameter of 921 mm, the stress ranges from 178 to 189 MPa for a conventional carbide plate and from 431 to 449 MPa for SSTP. For a diameter of 931 mm, the stress ranges from 431 to 449 MPa for a conventional plate and from 431 to 449 MPa for SSTP. MPa.

The high degree of convergence between calculated and experimental data during compression tests convinces us of the validity of the developed methodology and calculation program based on SSTP.

From these positions, SSTP proved more acceptable and reliable for increasing the voltage and improving the surface. Thus, the experimental tests confirmed the reliability of stress and strain calculations based on microstructural image distortion analysis using modern digital and computational technologies.

The degree of convergence between calculated and experimental stress data during testing convinces us of the correctness of the developed methodology and calculation program. It also confirms that during wheelset machining, surface hardening occurs, and the initial stress decreases from the factory value of 750 MPa to 449 MPa. Therefore, experimental tests verified the accuracy of stress and strain calculations based on microstructural image distortion using advanced digital and computer technologies.

A slight increase in stress accompanies this hardening of the surface. The main cause of defects on the wheelset surface was found to be violations of casting and cooling technologies. Microstructural compression tests revealed a reduction in yield strength in certain surface layers. The initial yield strength of the metal was not reached; no defects were found in other processed layers.

Thus, in the metal processing process during regrinding of wheel pairs, the surface of steel st2t is strengthened, and the stress on the axis is simultaneously reduced. Also, the main factor in the appearance of a defect on the surface of the wheel pair was a violation of lithium and cooling technology. Microstructural analysis experiments under compression revealed a decrease in fluidity in individual layers and on the surface. The initial values of metal fluidity are not achieved, and no defects were detected in other layers of processing. This conclusion will be useful to the entire world machine-building industry engaged in the processing and regrinding of metals and alloys. This conclusion has led to more widespread use of SSTP across the global metal-processing industry. The decrease in stress in the metal is caused not only by a decrease in the size of the cutting material sample, but also by the quality of casting and the conditions of uneven cooling of the blanks.

7. Results

The experimental results demonstrate that cutting parameters significantly affect surface hardness and roughness.

Increasing cutting depth and feed rate increases surface hardness, whereas excessive spindle speed reduces it due to thermal softening.

Optimal machining conditions were identified as:
n = 27 rpm
t = 2.5 mm
s = 6 mm/rev

Under these conditions, hardness values up to 360–370 HB were achieved.

The response surface analysis confirms a nonlinear relationship between cutting parameters and surface properties, indicating the importance of selecting balanced machining regimes.

8. Conclusion

The study confirms that the use of dual interchangeable carbide inserts (DICI) significantly improves machining performance in wheelset reprofiling.

The proposed approach increases surface hardness, stabilizes cutting conditions, and enhances tool life. Experimental results demonstrate that optimized cutting parameters allow effective control of surface integrity.

Microstructural analysis revealed the formation of compressive stresses and a reduction in internal stress gradients, which positively affects эксплуатационные свойства колесных пар.

The implementation of DICI provides both technological and economic advantages, making it a promising solution for railway maintenance and metalworking applications.

References

Alnejaili, T., Drid, S., Mehdi, D., Chrifi-Alaoui, L., Belarbi, R., & Hamdouni, A. (2015). Dynamic control and advanced load management of a stand-alone hybrid renewable power system for remote housing. *Energy Conversion and Management*, *105*, 377-392. https://doi.org/10.1016/j.enconman.2015.07.080

Ameen, N. H. (2024). Investigation of Material Nonlinearities in Surface Effects and Bulk on the Vibration Characteristics of Nanobeams. *Reports in Mechanical Engineering*, *5*(1), 68-81. https://doi.org/10.31181/rme413

Bellavista, P., Giannelli, C., Mamei, M., Mendula, M., & Picone, M. (2021). Application-driven network-aware digital twin management in industrial edge environments. *IEEE transactions on industrial informatics*, *17*(11), 7791-7801. https://doi.org/10.1109/TII.2021.3067447

Dewangan, S. K., Kumar, P., & Jha, S. K. (2019). Optimization of quality and productivity of wire EDM by using L9 orthogonal array. In *Advances in Industrial and Production Engineering: Select Proceedings of FLAME 2018* (pp. 93-100). Springer. https://doi.org/10.1007/978-981-13-6412-9_9

Kalavathi, V., & Bhuyan, R. (2018). Optimization of process parameters in wedm process on two workpieces of materials Hardox-400 and hardox-500. *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) vol*, *8*(4), 71-82. https://tinyurl.com/ut43uh7d

kumar Naik, D., & Maity, K. (2018). An Optimization and Experimental Analysis of Plasma Arc Cutting of Hardox-400 using Taguchi based Desirability Analysis. *Materials Today: Proceedings*, *5*(5), 13157-13165. https://doi.org/10.1016/j.matpr.2018.02.306

Li, D. (2024). Second Law of Engineering Thermodynamics. In *Analytical Thermodynamics* (pp. 235-253). Springer. https://doi.org/10.1007/978-3-030-90517-0_4

Maksimov, R. O., Zhileykin, M. M., Keller, A. V., Shadrin, S. S., Makarova, D. A., & Furletov, Y. M. (2025). Equalizing Leaf Spring Vehicle Suspension Synthesis Technologies Based on Modern Mathematical Simulation Modeling. *Reports in Mechanical Engineering*, *6*(1), 91-101. https://doi.org/10.31181/rme454

Senthilkumar, N., Tamizharasan, T., & Anandakrishnan, V. (2014). Experimental investigation and performance analysis of cemented carbide inserts of different geometries using Taguchi based grey relational analysis. *Measurement*, *58*, 520-536. https://doi.org/10.1016/j.measurement.2014.09.025

SHARIF, S., RAHIM, E. A., MOHRUNI, A. S., & JAWAID, A. (2007). Effect of Edge Geometry on PVD-TiN Coated Carbide Tools when Face Milling Titanium Alloy, Ti-6246. In *Proceedings of International Conference on Leading Edge Manufacturing in 21st century: LEM21 2007.4* (pp. 7A107). The Japan Society of Mechanical Engineers. https://doi.org/10.1299/jsmelem.2007.4.7A107

Sherov, K., Ainabekova, S., Kuanov, I., Myrzakhmet, B., Bekzhanov, Y., Gabdyssalik, R., Mazdubay, A., Kamarov, A., & Sherov, A. (2022). Research of temperature distribution in the process of thermo-frictional cutting of titanium alloy TI-5553. *Journal of Applied Engineering Science*, *20*(2), 400-407. https://doi.org/10.5937/jaes0-32723

Wang, G.-F., & Feng, X.-Q. (2007). Effects of surface elasticity and residual surface tension on the natural frequency of microbeams. *Applied physics letters*, *90*(23). https://doi.org/10.1063/1.2746950

Wang, G.-F., & Feng, X.-Q. (2009). Surface effects on buckling of nanowires under uniaxial compression. *Applied physics letters*, *94*(14). https://doi.org/10.1063/1.3117505

Wang, K., & Wang, B. (2011). Vibration of nanoscale plates with surface energy via nonlocal elasticity. *Physica E: Low-dimensional Systems and Nanostructures*, *44*(2), 448-453. https://doi.org/10.1016/j.physe.2011.09.019

Zhao, D., Wang, J., & Xu, Z. (2021). Surface effect on vibration of timoshenko nanobeam based on generalized differential quadrature method and molecular dynamics simulation. *Nanomanufacturing and Metrology*, *4*(4), 298-313. https://doi.org/10.1007/s41871-021-00117-3

Zhao, K., Pharr, M., Hartle, L., Vlassak, J. J., & Suo, Z. (2012). Fracture and debonding in lithium-ion batteries with electrodes of hollow core–shell nanostructures. *Journal of Power Sources*, *218*, 6-14. https://doi.org/10.1016/j.jpowsour.2012.06.074