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Prediction of tool wear intensity during machining of titanium nickelide TN-1

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ABSTRACT

Introduction. One of the crucial criteria for evaluating the effectiveness of the chosen strategy for machining blanks is the tool wear intensity. Reducing the intensity of tool wear leads to a reduction in production costs related to cutting tool expenditures and an improvement in overall productivity. **The purpose of this** work is to reduce tool wear intensity during the machining of a blank manufactured from the shape memory alloy titanium nickelide *TN-1*. **Methods.** As part of this research, a complete three-factor turning experiment was conducted on the alloy blank to determine the cutting insert wear intensity over a wide range of cutting conditions. During the tests, the geometric parameters of the resulting chips, specifically thickness and width, were measured. By constructing graphs representing the dependencies of the chip parameters, approximating these dependencies, and assessing the reliability of each approximation, a key parameter was identified for developing a methodology to predict tool wear intensity. **Results and discussion.** The study demonstrates that for predicting the cutting insert wear intensity when turning a titanium nickelide *TN-1* blank, it is advisable to use the dependency on the resulting chip thickness. The established mathematical dependency is described by a system of equations that allows for the determination of the cutting insert wear intensity and the calculation error. The probability of accurately predicting the true value of tool wear intensity within the specified range is at least 87.5% at a 95% confidence level, which indicates sufficient practical accuracy. The essence of the methodology developed within this study for predicting the cutting insert wear magnitude lies in performing a test cut to obtain a chip whose thickness is then used to calculate the wear intensity magnitude and the most probable absolute error based on the established dependencies. Additionally, the study establishes that the wear intensity dependency exhibits a minimum point. This circumstance allowed for the establishment of the minimal possible wear intensity during *TN-1* alloy machining, as well as the associated calculation error: $\delta_{Vmin} = (0.432 \pm 0.096)\cdot 10^{-3}$ mm^{-2}. For an optimal chip thickness of $a = 0.34$ mm, the closest tested mode yielding a comparable wear intensity of $0.475\cdot 10^{-3}$ mm^{-2} is: cutting speed 5 m/min, feed rate 0.2 mm/rev, depth of cut 0.3 mm. The chip thickness for this mode was 0.4 mm.

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Introduction

The intensity of tool wear during manufacturing processes in mechanical engineering plays a crucial role in evaluating the efficiency of selected machining strategies. Low wear intensity indicates that the machining conditions are rationally chosen in terms of tool life. A decrease in tool wear intensity reduces production costs related to tool expenses and increases overall productivity [1].

Therefore, manufacturers strive to minimize tool wear through various methods:

– using rational cutting parameters [2, 3, 4];

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– applying tools made from wear-resistant materials with optimized geometry and coatings [2, 5–8];
– lowering the temperature in the cutting zone [9, 10–13];
– physical and chemical treatment of tools or workpieces to alter their properties prior to or during machining [14–18].

However, tool wear intensity depends on numerous factors, making it variable even under constant machining conditions. Despite its unpredictability, research efforts have been directed towards forecasting it. Possible approaches include:
– empirical relationships derived from preliminary experimental studies [20–22];
– artificial intelligence and machine learning applications [23, 24];
– experimental identification of dependencies between controlled factors and wear intensity for specific machining scenarios [25–27].

The first approach suffers from low accuracy due to random influences such as material composition, coating quality, equipment performance, and coolant characteristics. The second option is costly. Thus, the third approach was adopted in this study as the most reasonable.

As an example of the processed material, titanium nickelide (nitinol) grade ***TN-1*** was selected because of its limited research coverage and importance in industries requiring shape memory alloys, particularly aerospace. Dry turning was used to eliminate external influences and align with industrial practices.

In view of the above considerations, ***the purpose of this study*** was to reduce tool wear intensity during the machining of titanium nickelide *TN-1*. To achieve this goal, the several following ***tasks*** were addressed:
– Conduct experimental investigations of tool wear intensity under different machining conditions.
– Select a parameter for analyzing process behavior and identifying its correlation with tool wear intensity.
– Establish a dependency between tool wear intensity and the chosen parameter.
– Develop a methodology for predicting tool wear intensity and provide recommendations for selecting efficient machining settings.

Methods

The chemical composition and properties of the material used for the research are presented in Tables 1 and 2 respectively [28–30].

An example of an aerospace product where the *TN-1* alloy is applied is a single-use valve shown in Fig. 1 [31]. The operating principle of this valve is based on restoring the original shape of a pre-deformed (compressed) pusher 5 when heated, causing the tailpiece 8 to rupture at its groove. As a result, the working medium (gas or liquid) flows through the resulting gap towards the nipple 4.

From Fig. 1**,** it can be seen that the pushers 5 are bodies of rotation. Therefore, their manufacture involves turning operations.

Table 1

Chemical composition of the *TN-1* alloy, under *TU 1-809-394-84* (% by weight)

Ni	*Ti*	Impurities (not more than)							Sum of other impurities (not more than)
		C	*Co*	*Fe*	Si	N	O	H	
53.5-56.5	Bal.	0.1	0.2	0.3	0.15	0.05	0.2	0.013	0.3

Table 2

Mechanical properties of the *TN-1* alloy

ρ, kg/m^3	$\boldsymbol{\sigma_v}$, MPa	$\boldsymbol{\sigma_{0.2}}$, MPa	**δ**, %	***E***, GPa	**HV**	$\boldsymbol{T_{mel}}$, °C	**λ**, W/(m·K)	***c***, J/(kg·K)
6,450–6,500	588	294	>10	33	331±42	1,250-1,310	8.6-18	456

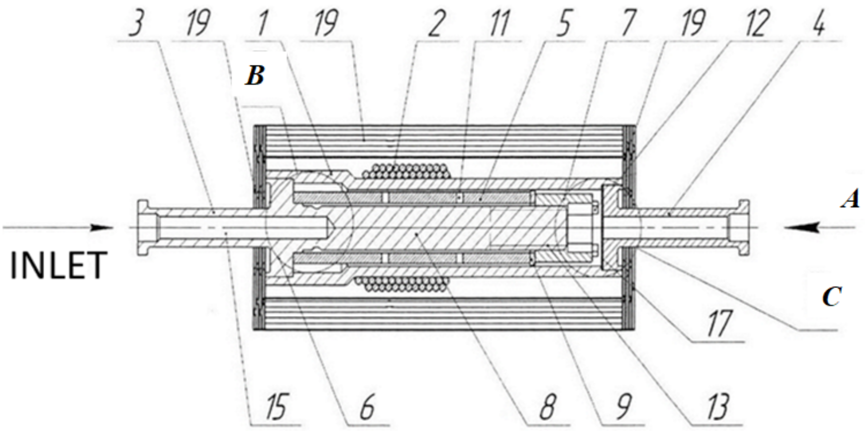


Fig. 1. Single-acting valve

The evaluation of wear intensity was carried out on a *UTS6* bench-type lathe with a computerized *CNC* system. Turning was chosen as the most common method for manufacturing products from the *TN-1* alloy. A cutting tool with indexable cemented carbide inserts *CCMT09T308-EM* with a multilayer *PVD* coating of total thickness of 4 μm based on *AlTiN* (aluminum titanium nitride) (*ZCC Cutting Tools*, China) was used. The substrate material of these inserts is an ultrafine-grained cemented carbide *YBG205* consisting of cobalt, tungsten carbides, and titanium carbides. The percentage content of each component is a trade secret of the manufacturer. These cutting inserts are intended for machining the following groups of materials up to 55 *HRC* hardness: carbon steels, alloy steels, corrosion-resistant steels, titanium alloys, and heat-resistant alloys.

The geometric parameters of the tool were as follows: $\gamma = 0°$, $\alpha = 7°$, $\varphi = 90°$, $\varepsilon = 80°$, $r = 0.4$ mm. The diameter of the workpiece was 10 mm.

Cutting conditions during testing were selected based on those commonly employed in finishing and semi-finishing operations in production, specifically:

– cutting speed: from 5 to 30 m/min;
– feed rate: from 0.03 to 0.2 mm/rev;
– depth of cut: from 0.1 to 0.3 mm.

It should be noted that since determining the direct relationship between cutting parameter settings and the wear intensity of the insert was not part of the study objectives, it was decided to limit the number of experiments by using only the extreme levels of factor variation. However, different combinations of selected factors provided varying cutting conditions, leading to different values of the characteristic parameter describing the process. This allowed for constructing a graph showing the dependence of tool wear intensity on the chosen parameter.

Thus, a full three-factor experiment was conducted. During the tests, the controlled parameter was the wear of the cutting insert on the rear face, which was measured using a calibrated digital microscope. The limiting value of wear was set at 0.3 mm, corresponding to the average criterion for wear under finishing and semi-finishing conditions. Since the adopted limiting wear value significantly exceeds the thickness of the coating on the cutting insert, durability assessment was performed for the entire tool assembly without considering the influence of the coating layer. Subsequently, the results obtained were used to determine the wear intensity δ_v of the cutting insert relative to the volume of material removed from the workpiece:

$$\delta_V = \frac{h_r}{V_{rem}}, \tag{1}$$

where h_r is the tool wear on the rear face, mm; V_{rem} is the volume of removed stock material, mm^3.

However, conducting durability tests is labor-intensive and resource-consuming, so it is reasonable to derive a mathematical dependency that allows predicting wear intensity based on a parameter that is easily measurable during processing and does not require expensive equipment for its measurement.

One such factor characterizing the cutting process is the generated chip. Its main parameters – thickness (***a***) or width (***b***) – in this study were measured using a calibrated digital microscope.

During the investigations, a specific machining mode was established. After completing a tool pass, the cutting insert was removed from the tool holder, and the wear on the rear face was measured. For the chip produced, its thickness and width were also measured. The recorded values were entered into a table, after which the insert was reinstalled into the holder, and another pass was executed. Testing continued until the maximum permissible wear level was reached, after which another machining mode was set.

To enhance the reliability of the experimental findings, each test was repeated five times, followed by calculating the arithmetic mean values of wear intensity and chip parameters, which were then recorded in the table.

Results and Discussion

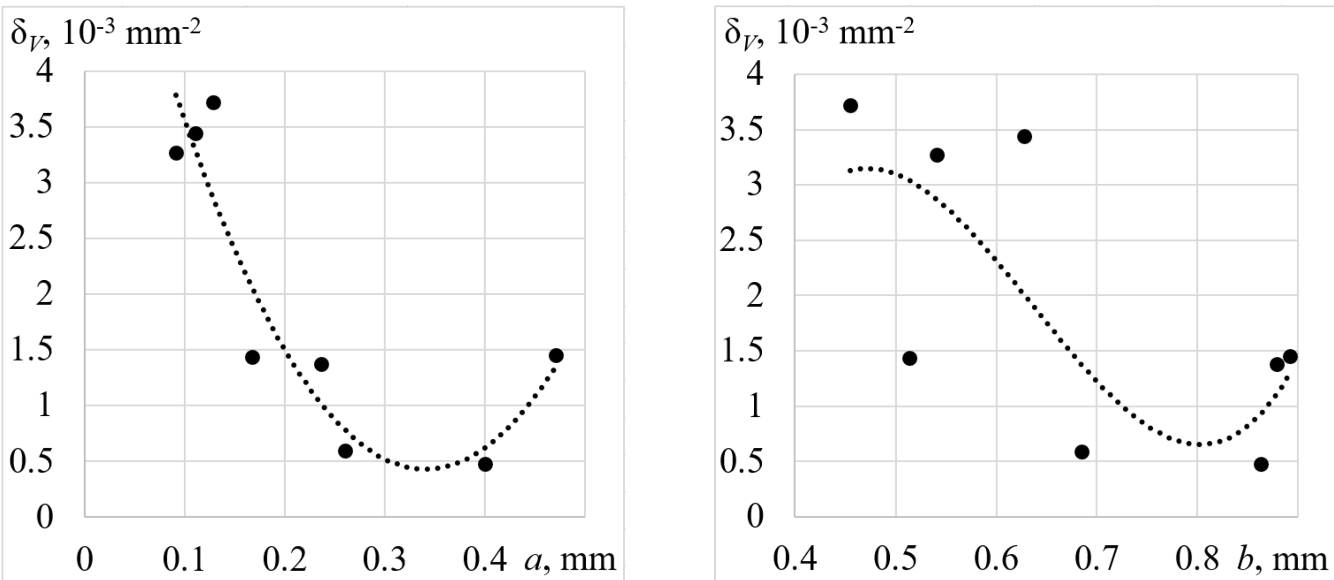
The test results, including values of insert wear intensity and measurements of chip thickness (*a*, mm) and width (*b*, mm), are summarized in Table 3.

Based on provided data, graphs representing the dependencies $\delta_v = f(a)$ and $\delta_v = f(b)$ were constructed, as depicted in Fig. 2.

Table 3

Test results

Experiment number	***V***, m/min	***S***, mm/rev	***t***, mm	δ_V, 10^{-3} mm^{-2}	***a***, mm	***b***, mm
1	5	0.03	0.1	0.594	0.260	0.685
2	30	0.03	0.1	3.271	0.092	0.541
3	5	0.2	0.1	1.435	0.167	0.514
4	30	0.2	0.1	3.723	0.129	0.455
5	5	0.03	0.3	1.45	0.471	0.892
6	30	0.03	0.3	3.444	0.111	0.628
7	5	0.2	0.3	0.475	0.400	0.863
8	30	0.2	0.3	1.377	0.237	0.879



a *b*

Fig. 2. Dependence graphs $\delta_V = f(a)$ (*a*) and $\delta_V = f(b)$ (*b*)

Evaluation of these dependencies using *MS Excel* tools yielded the coefficient of determination (R^2), which amounted to:

– for the graph $\delta_v = f(a)$ – $R^2 = 0.8653$;

– for the graph $\delta_v = f(b)$ – $R^2 = 0.4943$.

Therefore, for forecasting wear intensity, it is advisable to use the first dependency – $\delta_v = f(a)$ – since it provides greater calculation accuracy. The established dependency is described by the empirical formula:

$$\delta_v = 54.0785a^2 - 36.8231a + 6.7004. \quad (2)$$

To estimate the error, previously measured chip thicknesses were substituted into Equation (2); wear intensity was calculated, and the relative error ε compared to experimental data was determined. The obtained data are presented in Table 4.

Table 4

The results of calculations of the wear intensity

Experiment number	***a***, mm	δ_V (experimental), 10^{-3} mm^{-2}	δ_V (calculated), 10^{-3} mm^{-2}	**ε**, %
1	0.260	0.594	0.782	31.67
2	0.092	3.271	3.784	15.68
3	0.167	1.435	2.059	43.49
4	0.129	3.723	2.862	−23.14
5	0.471	1.45	1.354	−6.65
6	0.111	3.444	3.292	−4.42
7	0.400	0.475	0.621	30.63
8	0.237	1.377	1.016	−26.18

Evaluation of the calculation results indicates that determining specific wear intensity values using the derived dependency yields significant errors ranging from 4.42 to 43.49 %. This discrepancy arises from the relatively small dimensions of the measured chips, low values of wear intensity, and heterogeneity of both tool and workpiece materials, influencing their properties. Consequently, it is essential not only to establish the dependency of wear intensity but also to assess the error associated with its calculation using the derived formula. To achieve this objective, absolute errors $\Delta\delta_V$ were computed, and a graph illustrating their dependency on the thickness of the formed chips was plotted, as displayed in Fig. 3. Points exhibiting significant deviations from the constructed dependency were discarded and excluded from further analysis as erroneous outliers.

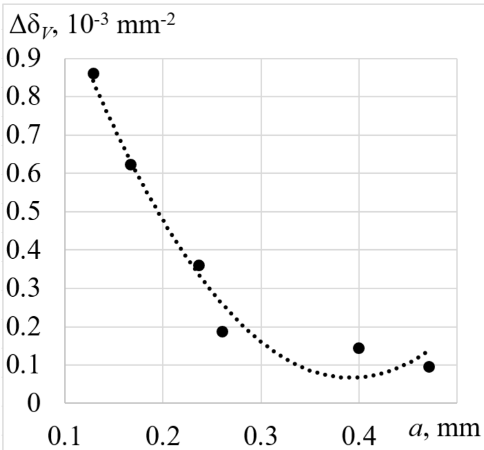


Fig. 3. Dependency graph $\Delta\delta_V = f(a)$

The evaluation of the obtained dependence showed that its coefficient of determination is $R^2 = 0.9697$**.** The graph presented in the figure is described by the formula:

$$\Delta\delta_V = 11.179a^2 - 8.7612a + 1.7833. \quad (3)$$

Thus, the final dependency for predicting tool wear intensity when machining a titanium nickelide *TN-1* workpiece can be described by the following system of equations:

$$\begin{cases} \delta_V = 54.0785a^2 - 36.8231a + 6.7004, \\ \Delta\delta_V = 11.179a^2 - 8.7612a + 1.7833. \end{cases} \quad (4)$$

Graphically, the established system of equations can be represented as curves bounding the scatter of values of cutting insert wear intensity during turning of a titanium nickelide ***TN-1*** workpiece (Fig. 4).

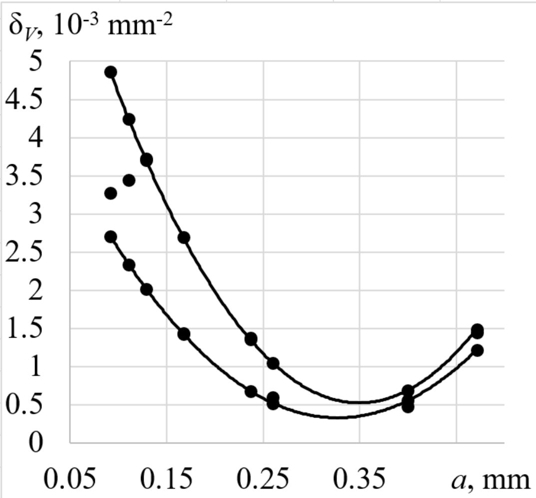


Fig. 4. Variation in tool wear intensity during turning of titanium nickelide *TN-1*

Evaluation of this figure through comparison with experimental results has shown that the probability of an actual value of tool wear intensity falling within the given area is no less than 87.5% at a confidence level of 95 %. This indicates sufficient accuracy for practical use.

Furthermore, it **is** evident that the wear intensity dependence exhibits a minimum point. This suggests the possibility of determining an optimal or range of optimal values for wear intensity if the maximum permissible value is known.

To determine the optimal wear intensity value, Equation (2) was differentiated with respect to chip thickness ***a*** and set equal to zero. Solving the resulting equation allowed for establishing the minimal wear intensity value for the case under consideration, along with the calculation error according to expression (3):

$$\delta_{V\min} = (0.432 \pm 0.096)\cdot 10^{-3}\ \text{mm}^{-2}.$$

The optimal chip thickness value is ***a*** = 0.34 mm.

Among the tested modes, the one providing comparable wear intensity of the cutting insert (0.475×10^{-3} mm^{-2}) was found to be: cutting speed of 5 m/min, feed rate of 0.2 mm/rev, depth of cut of 0.3 mm, leading to a chip thickness of 0.4 mm.

In summary, the methodology for forecasting tool wear intensity during machining of titanium nickelide *TN-1* or similar alloys is as follows. Prediction involves performing a trial pass of the tool to obtain chips whose thickness will allow calculating both the magnitude of wear intensity and the most probable absolute error using the dependencies provided above (Equation 4). Performing such operations significantly reduces testing time and expenses on cutting tools.

It should also be noted that the identified dependencies of tool wear intensity under dry machining conditions without the application of coolant-lubricants correlate well with modern trends toward environmentally safe mechanical processing technologies (dry machining, minimum quantity lubrication – *MQL*). These findings may not only assist in selecting rational cutting parameters but also contribute to forming the methodological foundations for modeling surface plastic deformation processes, particularly burnishing. This opens up possibilities for integrating the proposed approach into tasks related to the prediction of surface layer properties, including roughness and wear resistance.

Conclusions

The conducted research achieved the following results:

– Experimental determination of tool wear intensity values for various turning regimes of titanium nickelide *TN-1* workpieces;

– selection of chip thickness as the parameter characterizing the process due to its significant impact on the precision of tool wear intensity calculations;

– establishment of an empirical relationship between tool wear intensity and chip thickness. The dependence is parabolic in nature, allowing identification of the minimum point and the corresponding minimum possible tool wear intensity;

– development of a method for predicting tool wear intensity based on chip thickness when machining titanium nickelide *TN-1*. The recommended machining regime is: cutting speed of 5 m/min, feed rate of 0.2 mm per revolution, depth of cut of 0.3 mm.

These results enable extrapolation of established cutting regimes to other types of cutting machining methods applicable to titanium nickelide and its analogs, subject to certain assumptions. Additionally, the morphology and characteristics of chips serve as diagnostic indicators reflecting the mechanical properties of the material, such as strength and ductility. The established correlations suggest the potential utilization of these parameters for predictive analysis in surface plastic deformation (*SPD*) processes. Consequently, they could act as criteria for choosing rational *SPD* regimes aimed at achieving desired surface-layer properties. Considering also the influence of the surface condition after machining on subsequent *SPD* operations [32], the presented outcomes might be integrated into reverse-modeling systems focused on geometrical product specification (*GPS*) characteristics optimization during burnishing. Such integration ensures continuity and systematicity in ongoing investigations.

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Conflicts of Interest

The authors declare no conflict of interest.