

Letters

Cutting performance of TiAlN-based thin films in micromilling high-speed steel AISI M3:2



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ARTICLE INFO

Article history:

Received 4 October 2023

Received in revised form 19 December 2023

Accepted 12 January 2024

Available online 23 January 2024

Keywords:

Magnetron sputtering

TiAlN

TiAlSiN

TiAlTaN

Micromilling

Hard machining

ABSTRACT

Micromilling high-speed steel offers high precision in shape and geometry. However, the service life greatly depends on the wear resistance of protective thin films. In comparison to TiAlN, TiAlSiN and TiAlTaN thin films offer enhanced wear resistance for difficult-to-machine materials. Employing a hybrid process that combines direct current magnetron sputtering (dcMS) and high power pulsed magnetron sputtering (HiPIMS) enhances the properties of these films. In cutting tests, it is demonstrated that TiAlSiN and TiAlTaN outperform TiAlN in micromilling of high-speed steel AISI M3:2. Notably, dcMS/HiPIMS-TiAlSiN stands out by having the lowest reduction in cutting forces combined with reduced wear.

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1. Introduction

Beyond traditional machining methods, micromachining emerges as a promising technological approach in the field of die and mold manufacturing. Micromilling of hardened tool steels holds the potential to achieve high accuracy of dimension and shape for filigree geometries combined with high surface quality [1]. Moreover, this process induces residual compressive stresses within the sub-surface zone of the workpiece [2,3], which has a positive effect on the fatigue resistance and adhesion of subsequent applied protective thin films [3,4]. Consequently, this contributes significantly to an improved performance and enhanced service life of the fabricated components.

To enhance performance and service life, micromilling cutters are coated with wear-resistant thin films [5]. Titanium aluminum nitride (TiAlN) is commonly used as thin film material due to its high hardness and wear resistance [6]. Since the requirements are constantly increasing due to difficult-to-machine workpiece materials, current research is focused on improving the thin film properties. Titanium aluminum silicon nitride (TiAlSiN)

demonstrates higher resistance against wear and oxidation compared to TiAlN [7,8]. Titanium aluminum tantalum nitride (TiAlTaN), with higher hardness, thermal stability, and oxidation resistance than TiAlN, represents an auspicious alternative [9]. These quaternary nitride systems are highly promising thin film systems for micromilling hardened tool steels.

Among the physical vapor deposition techniques, magnetron sputtering is a widely used method for depositing TiAlN-based thin films on micro milling cutters [10]. Direct current magnetron sputtering (dcMS) stands as the simplest and most cost-effective sputtering method, providing moderate hardness along with relatively high deposition rates [11]. In contrast, high power pulsed magnetron sputtering (HiPIMS) produces dense thin films with high hardness, but with complex process control and low deposition rates [12]. Hybrid dcMS/HiPIMS processes combine the advantages of each and allow the synthesis of thin films with improved properties [13,14].

Hence, the use of a hybrid dcMS/HiPIMS process to deposit TiAlN-based thin films is a promising approach to improve the cutting performance and service life of micromilling cutters. The wear resistance and cutting performance of dcMS/HiPIMS-TiAlN, dcMS/HiPIMS-TiAlSiN, and dcMS/HiPIMS-TiAlTaN coated micro end mills are evaluated in micromilling of hardened high-speed steel AISI

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M3:2 (HS6–5–3). A comparative analysis is made with tools coated with the corresponding dcMS thin film systems.

2. Materials and methods

TiAlN, TiAlSiN, and TiAlTaN thin films were deposited on micro end mills using a customized PVD device METAPLAS.DOMINO kila flex (Oerlikon Balzers Coating Germany GmbH, Germany). The setup included two magnetron cathodes equipped with $Ti_{50}Al_{50}$, $Ti_{40}Al_{40}Si_{20}$, or $Ti_{40}Al_{40}Ta_{20}$ targets (Plansee SE, Germany). The magnetron cathodes were operated in either dcMS or hybrid dcMS/HiPIMS mode. The deposition rate, chemical composition, and hardness values of both the dcMS and dcMS/HiPIMS thin films are summarized in Table 1. For each thin film, two fluted micro end mills with a diameter of $D = 1$ mm and a corner radius of $r_c = 50$ μm , derived from the Peakcook Series 599 (Zecha Hartmetall-Werkzeugfabrikation GmbH, Germany), were used.

The machining tests were performed on the machine tool HSPC 2522 (Kern Microtechnik GmbH, Germany). As workpiece material served the hardened and tempered powder metallurgical high-speed steel AISI M3:2 with a hardness of (62 ± 1) HRC. Dry down milling was carried out with a depth of cut $a_p = 25$ μm , a width of cut $a_e = 200$ μm , a feed per tooth $f_z = 25$ μm , and a cutting speed $v_c = 120$ m/min. The cutting forces were measured with a piezoelectric multicomponent dynamometer MicroDyn 9109 AA (Kistler Instrumente AG, Switzerland) at a sampling rate of 100 kHz. The assessment of the width of the flank wear land VB was conducted using a digital microscope VHX-5000 (Keyence Corporation, Japan) for wear analysis.

3. Results and discussion

Fig. 1 shows SEM micrographs of the morphology of the thin films on flat cylindrical WC–Co substrates and the initial state of coated micro end mills. All dcMS thin films exhibit a columnar-like structure, with dcMS–TiAlSiN showing a more compact morphology. In contrast, dcMS/HiPIMS–TiAlN and dcMS/HiPIMS–TiAlTaN have denser structures with fewer columnar-like features. In particular, dcMS/HiPIMS–TiAlSiN possesses a glass-like morphology without columns. The integration of HiPIMS into the hybrid dcMS/HiPIMS process increases the ionization density, thereby intensifying ion bombardment during film growth and promoting denser structures [15]. For dcMS/HiPIMS–TiAlSiN, the dense and glass-like morphology indicates the formation of the nanocomposite structure under intensive ion bombardment [16]. The addition of Si to TiAlN generally forms an amorphous Si_3N_4 phase, wherein TiAlN nanocrystallites are embedded [17]. With the exception of dcMS/HiPIMS–TiAlN with ~ 2.0 μm and dcMS–TiAlSiN with ~ 3.2 μm , all thin films have the target layer thickness of ~ 2.5 μm . Despite the different thicknesses of these two thin films, comparability of the thin film properties is still expected. SEM micrographs of the coated tools indicate minimal film delamination at the cutting edges. This is particularly noted for the dcMS/

HiPIMS thin films and may originate from high compressive stresses. Potential strategies to improve the adhesion at the cutting edge of micro end mills include adding interlayers in the thin film structure [18,19] or synchronizing the bias voltage with HiPIMS parameters for reduced compressive stresses [20].

The development of cutting forces over the considered travel path of the different coated tools during micromilling AISI M3:2 is shown in Fig. 2. Despite the comparatively low cutting parameters, there is a significant increase in the cutting force respectively the resultant force F_z over the service life considered, which is due to the high hardness and elevated carbide content of the steel [1]. These material properties lead to severe abrasive wear of the tools, resulting in a blunting of the cutting edge. This can be observed by the significant increase in passive forces, which can be attributed to increased plastic deformation and part-side material flow in respect of the major importance of the cutting edge shape in micromachining [2]. Furthermore, this circumstance also results in a cutting edge offset, which reduces the effective cutting depth to the point of causing a run-out of the cutting edge engagement. As a result, the effective cutting depth falls below the minimum chip thickness, resulting in a ploughing dominated process with almost no material removal, as can be clearly seen from the predominant passive forces. Fig. 3 displays the width of the flank wear land VB and SEM micrographs of the worn cutting edges. The clearance angle, combined with the thin film thickness, results in a portion of the wear mark located not in the substrate but within the thin film. This was differentiated in the analysis, resulting in VB values for both the substrate and the thin film. It is noted that both the thin film material itself and the sputtering techniques, especially for TiAlN and TiAlSiN, have a significant impact on the cutting force and wear behavior.

Both TiAlN thin films experienced premature tool failure, with dcMS/HiPIMS–TiAlN achieving a longer travel path of $l_f = 5.8$ m compared to dcMS–TiAlN with $l_f = 4$ m. Upon reaching the end of their service lives considered, both coated tools showed comparable widths of the wear land of $VB = (102 \pm 1)$ μm and $VB = (102 \pm 3)$ μm with an extensive abrasive wear along the flank face and blunting of the cutting corner. Despite similar hardness values for dcMS–TiAlN and dcMS/HiPIMS–TiAlN, the denser morphology of dcMS/HiPIMS–TiAlN is expected to provide enhanced wear resistance and, consequently, a longer service time than dcMS–TiAlN. In comparison to both TiAlN thin film systems, the addition of either Si or Ta to these films improves the cutting performance. In this context, both dcMS–TiAlTaN and dcMS/HiPIMS–TiAlTaN achieve a maximum travel path of $l_f = 7.7$ m with a similar progression of cutting forces and demonstrate a comparable service life. In this regard, both TiAlTaN thin films exhibit a comparable widths of the flank wear land of $VB = (101 \pm 2)$ μm and $VB = (98 \pm 2)$ μm . Therefore, the sputtering technique does not exert a significant effect on the cutting performance and wear behavior of TiAlTaN. For the Ta contents used, it is assumed that the mechanical properties and wear resistance of TiAlTaN are primarily influenced by the solution strengthening effect caused by Ta [21], rather than the sputtering

Table 1

Deposition rate, chemical composition, and hardness of TiAlN, TiAlSiN, and TiAlTaN deposited by either dcMS or dcMS/HiPIMS.

Thin film system	Deposition rate in $\mu\text{m}/\text{h}$	Chemical composition in at.-%					Hardness in GPa
		Ti	Al	Si	Ta	N	
dcMS–TiAlN	0.806 ± 0.003	22.3 ± 0.1	26.3 ± 0.2	–	–	51.4 ± 0.3	35.1 ± 2.9
dcMS/HiPIMS–TiAlN	0.483 ± 0.009	22.3 ± 0.3	25.8 ± 0.4	–	–	51.9 ± 0.6	36.0 ± 3.1
dcMS–TiAlSiN	1.169 ± 0.008	19.7 ± 0.4	22.5 ± 0.5	9.4 ± 0.2	–	48.4 ± 0.9	22.0 ± 2.4
dcMS/HiPIMS–TiAlSiN	0.867 ± 0.002	17.9 ± 0.4	21.5 ± 0.6	10.1 ± 0.2	–	50.5 ± 1.0	24.1 ± 2.2
dcMS–TiAlTaN	1.083 ± 0.003	20.0 ± 0.8	17.5 ± 0.6	–	12.7 ± 0.5	49.8 ± 1.9	38.4 ± 2.2
dcMS/HiPIMS–TiAlTaN	0.796 ± 0.005	19.7 ± 0.3	17.0 ± 0.1	–	12.3 ± 0.2	50.9 ± 0.6	41.2 ± 2.3

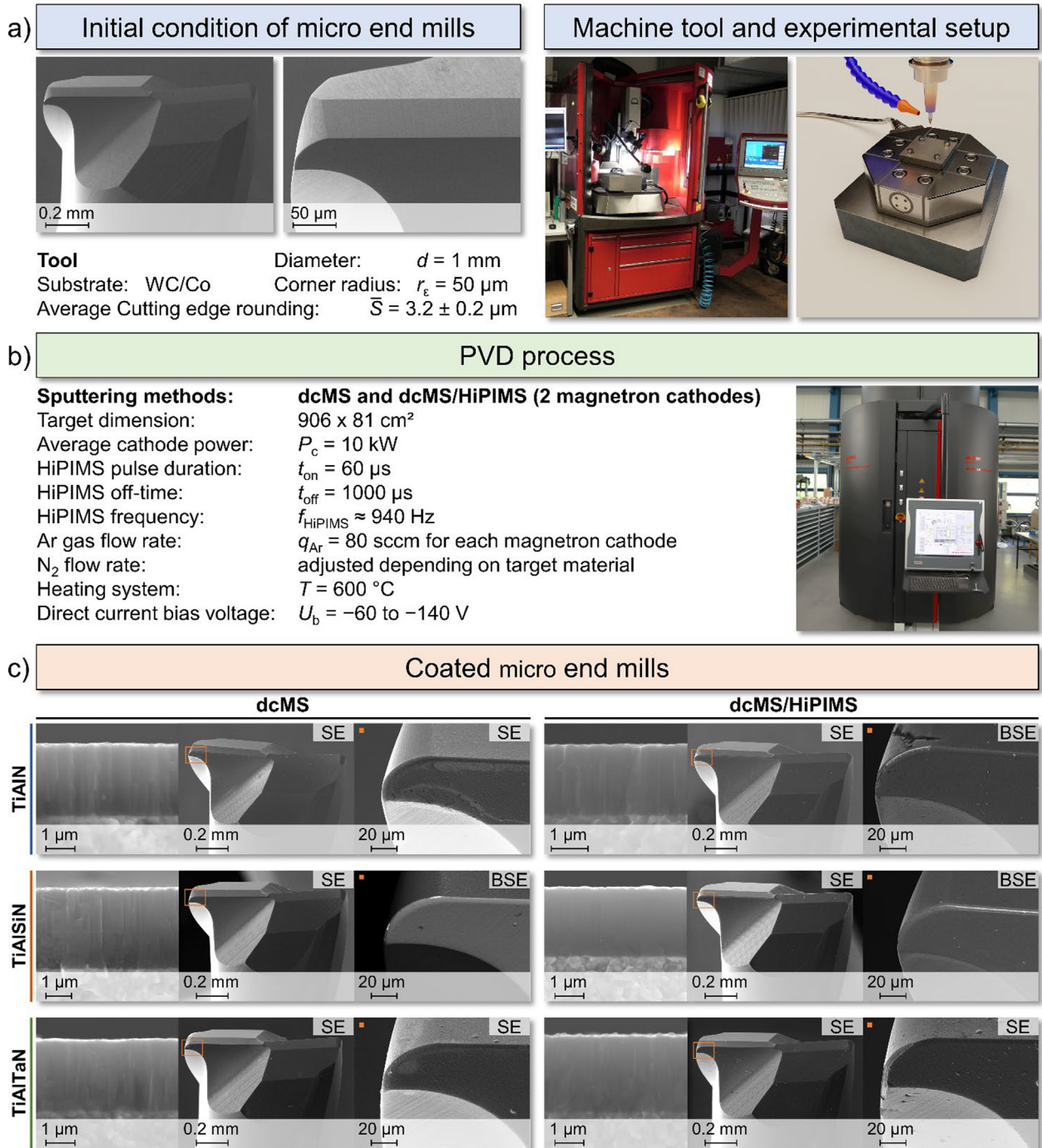


Fig. 1. (a) SEM micrographs of the initial condition of the micro end mills and images of the machine tool and experimental setup. (b) Overview of the used PVD process parameters. (c) SEM micrographs of the morphology of TiAlN, TiAlSiN, and TiAlTaN deposited by either dcMS or dcMS/HiPIMS, along with the coated condition of the micro end mills.

process with the chosen parameters. To further improve the properties of TiAlTaN thin films, an adjustment of the amount of Ta in combination with controlled ion irradiation with heavy Ta ions during the film growth, achieved by adapting the HiPIMS parameters, allows tailoring the chemical composition and structure [9,15,21].

On the contrary, the sputtering method significantly influences the cutting performance and wear behavior of the TiAlSiN thin films. Although dcMS-TiAlSiN achieves a longer travel path of $l_f = 5.8 \text{ m}$ compared to dcMS-TiAlN, it does not reach the end of

the travel path as dcMS-TiAlTaN, dcMS/HiPIMS-TiAlTaN, and dcMS/HiPIMS-TiAlSiN. The dcMS-TiAlSiN-coated tool exhibits a width of the flank wear land of $VB = (109 \pm 4) \text{ } \mu\text{m}$, slightly surpassing the values of the TiAlN and TiAlTaN thin film systems. In particular, among the different thin films, dcMS/HiPIMS-TiAlSiN significantly improves the wear resistance resulting in the lowest resultant force at the end of the considered service life, approximately 47 % lower compared to both dcMS-TiAlTaN and dcMS/HiPIMS-TiAlTaN thin films. In addition, the dcMS/HiPIMS-TiAlSiN-coated tool shows a low width of the flank wear land of

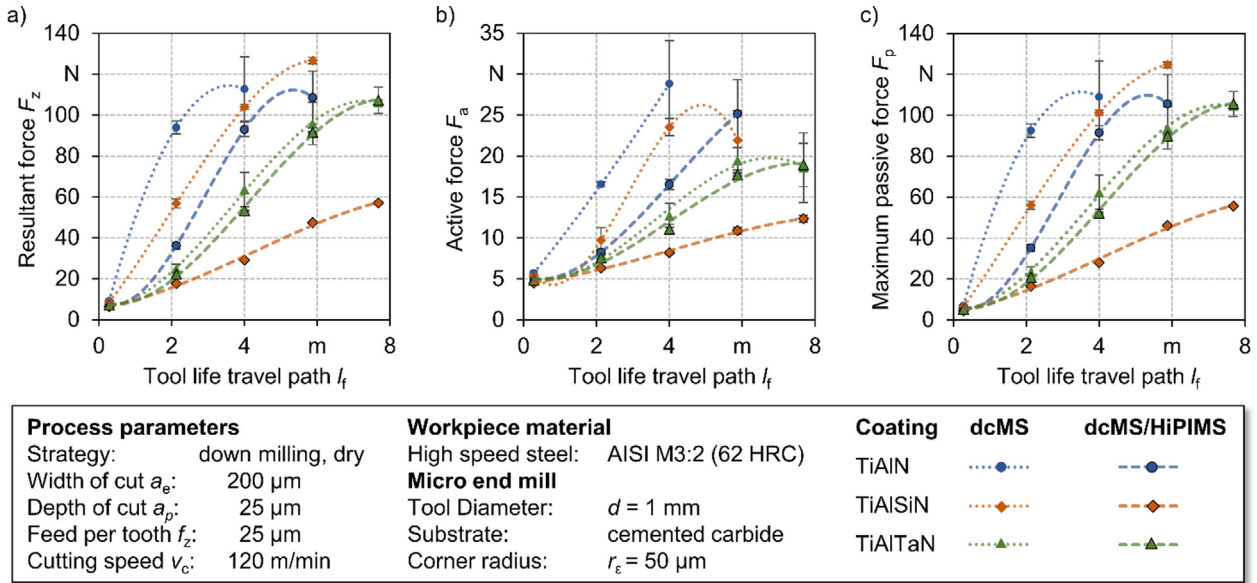


Fig. 2. Development of (a) the resultant force F_z , (b) the active force F_a , and (c) the passive force F_p over the tool life travel path l_f .

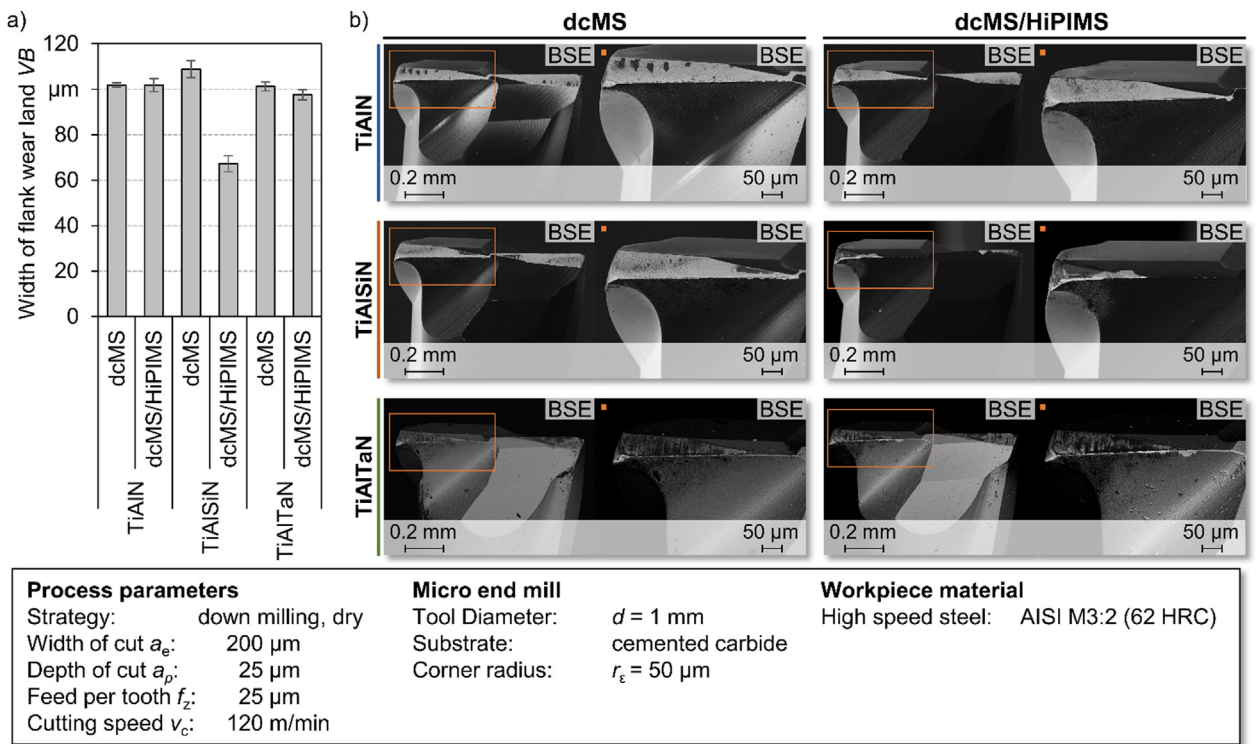


Fig. 3. (a) Characterization of the wear condition of tools based on the width of the flank wear land VB a) as well as (b) SEM micrographs of the worn cutting corner.

$VB = (67 \pm 4) \mu\text{m}$, representing a 33 % reduction compared to the maximum value of $VB \approx 100 \mu\text{m}$ observed for the coated tools. Although dcMS/HiPIMS-TiAlSiN has a lower hardness than dcMS/HiPIMS-TiAlN and dcMS/HiPIMS-TiAlTaN, it ensures a high cutting performance and wear resistance in micromilling hardened and tempered high-speed steel. On the one hand, this can be attributed to the higher oxidation resistance of TiAlSiN [8].

For cast high-speed steel HS6-5-2, a previous study estimated a micromilling process temperatures of $T \leq 200$ $^{\circ}\text{C}$ [22]. Nevertheless, a higher level of process temperatures can be expected with increasing workpiece hardness. Furthermore, the wear-induced blunting of the cutting edge caused the high hardness as well as

the finely dispersed carbides within the AISI M3:2 leads to a further increase in temperatures due to stronger plastic deformation and higher friction at the cutting edge. Consequently, the thermal stability of the thin films is of increasing importance over the period of use. On the other hand, the column-free, dense structure of dcMS/HiPIMS-TiAlSiN promotes a higher wear resistance [23].

4. Conclusions

The type of TiAlN-based thin film and also the sputtering techniques, especially for TiAlN and TiAlSiN, have a crucial impact on

the cutting performance and wear behavior of micro end mills in machining of hardened high-speed steel AISI M3:2. Due to the high hardness of the workpiece material, the coated tools were exposed to abrasive wear, causing a significant increase in cutting force. In particular, the TiAlN thin films are characterized by premature failure, while both TiAlTaN and TiAlSiN achieved extended tool life travel paths. With the exception of TiAlTaN, the dcMS/HiPIMS-TiAlN and dcMS/HiPIMS-TiAlSiN demonstrate a higher cutting performance than the corresponding dcMS thin films. Despite having a lower hardness than dcMS/HiPIMS-TiAlN and dcMS/HiPIMS-TiAlTaN, dcMS/HiPIMS-TiAlSiN showed improved wear resistance and achieved lower cutting forces to the end of the cutting path. The key findings are summarized as follows:

- The addition of Si or Ta to dcMS-TiAlN and dcMS/HiPIMS-TiAlN enhances wear resistance and cutting performance.
- At the end of the considered service life, dcMS/HiPIMS-TiAlSiN exhibits a 47 % reduction in cutting forces compared to dcMS-TiAlTaN and dcMS/HiPIMS-TiAlTaN.
- dcMS/HiPIMS-TiAlSiN demonstrates the lowest wear, with a 33 % reduction in the width of the flank wear land.

These findings underscore the substantial influence of both thin film properties and sputtering method in improving tool life and performance for micromilling of difficult-to-machine materials.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT and DeepL in order to improve language and readability. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Wolfgang Tillmann: Resources, Supervision, Writing – review & editing. **Alexander Leonard Meijer:** Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Visualization, Writing – original draft. **Timo Platt:** Writing – review & editing. **Dirk Biermann:** Resources, Supervision, Writing – review & editing. **Dominic Stangier:** Investigation, Writing – review & editing. **Nelson Filipe Lopes Dias:** Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge the financial support of the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation, Germany) within the project 445127534 (TI 343/187-1, BI 498/126-1).

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