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Comparative Performance Analysis of AlTiN, TiAlN, and TiSiN Coated Ball Nose Mills in Machining Stavax ESR

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Abstract

Coated carbide end mills have emerged as the essential cutting tools in CNC milling. The coated tools offer robustness, durability and good surface finishing, combining with a good milling setup in precision manufacturing. AlTiN, TiSiN and TiAlN-coated tools have been commercialised and become vital choices in the industries involving high-hardness metals. In the study, commercial AlTiN, TiSiN, and TiAlN coatings on 6 mm carbide ball-nose end mills were compared in terms of structural integrity in the 3-axis CNC mill machining of shallow curved Stavax ESR. A focused electron beam microscope was used to inspect the surface integrity of the post-milling ball noses. The experiments reveal that TiAlN-coated ball nose excel in durability, with minor coating delamination following AlTiN-coated tool. The TiSiN-coated ball-nose mill exhibited the lowest performance of all three coated tools. The mechanical breakage of the TiSiN coating suggests it is the least suitable option for the precision milling of shallow curved surfaces in this material grade.

Keywords: coating; tool durability; Stavax ESR; ball nose end mill: concave surface

1. Introduction

CNC milling has established itself as a cornerstone of modern industrial manufacturing and precision machining [1]. By effectively maintaining a required surface finish, minimising tool wear, and achieving a high material removal rate (MRR) in CNC milling, manufacturers can increase production rates. Thus, ensuring that the finished components meet strict dimensional and aesthetic standards [1]. The key factors that determine the quality of machined products include the selection of the machine tool, the specific characteristics and coatings of the cutting tools, and the cutting parameters [2]. In CNC milling, ball end mills are widely used because the tools can create many different shapes, from smoothing flat shapes to cutting curved surfaces [3]. Due to its flexibility, ball-end milling is widely employed for the fabrication of complex geometries in sectors such as aerospace, automotive, and mould manufacturing [4].

In the die and mould manufacturing, Stavax ESR is widely used due to its superior strength, thermal stability. machinability,and corrosion resistance [5,6]. The high hardness of Stavax makes it a challenging material to machine. This characteristic causes significant tool wear, which is a major concern in mould and die production. To ensure the machining process remains efficient, the use of ball-nose end mills with suitable coatings is needed. A previous study proved that coated tools performed better than uncoated tools in terms of greater machining stability and less wear, which minimises the overall cutting forces. While the uncoated carbide tools suffered from significant chipping, notch wear, and diffusion wear during the machining process. As a result, the parts machined with coated tools had smoother surfaces and smaller burrs [7,8]. Consequently, these coatings serve as a thermal and mechanical barrier that significantly reduces flank wear and abrasive degradation when machining high-hardness materials like Stavax ESR.

Commercial coated carbide cutting tools such as TiAlN, TiSiN and AlTiN are commonly used in CNC milling of hard materials due to their good mechanical properties [9,10,11]. The use of metal nitride films on carbide tools significantly increases the lifetime of tools in manufacturing due to their high hardness, high wear resistance, and excellent oxidation resistance. In terms of nanohardness, TiAlN coatings display a significantly higher value, relying on the Al mixture and deposition parameters. The inclusion of aluminium in AlTiN coatings increases the tools' hardness, wear resistance and oxidation resistance at high

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temperatures. TiSiN-coated tools come out with high hardness, excellent oxidation resistance at high temperatures, and superior resistance to abrasion and erosion. The studies concluded that AlTiN and TiAlN coatings are suitable for low surface roughness, while TiSiN coatings are preferred for high durability [12,13,14].

From the previous studies, the usage of AlTiN and TiAlN coatings results in lower surface roughness of the machined shape, while TiSiN coatings prolong the tool life. However, there have been limited studies concerning the comparison of standard industrial-grade coatings applied to ball-nose carbide tools for machining complex geometries. Hence, this paper focus on comparing the performance of three standard industrial-grade coatings applied on ball-nose carbide, namely TiAlN, TiSiN and AlTiN, while milling the curvature surface of Stavax ESR. This research also utilised affordable, standard tooling to provide practical information for industries in minimising manufacturing costs.

2. Research Method

Commercial coated 6 mm ball-nose carbides, namely TiAlN, TiSiN and AlTiN, purchased from a local supplier, were used in this study. The local sole distributor reveals nothing about the coating process used in the manufacturing of the purchased tools. Manufactured in China, the standard 2-flute carbide ball nose end mill is suitable for 3D profiling of Stavax ESR with pre-hardened hardness up to 35 HRC. Its geometric specifications include a 12 mm flute length, a 6 mm cutting diameter, a 3 mm radius, and a 30° helix angle, with a total length of 50 mm. Stavax ESR used in the experiments is manufactured by ASSAB through Electro-Slag Refining (ESR), a purification process that filters out impurities to create a clean metal [6]. The properties of a 50mm × 50mm × 30mm Stavax are presented in Table 1.

Table 1. Chemical composition of of Stavax ESR

Content	Typical analysis (wt) %
Carbon (C)	0.38
Silicon (Si)	0.9
Manganese (Mn)	0.5
Chromium (Cr)	13.6
Vanadium (V)	0.3

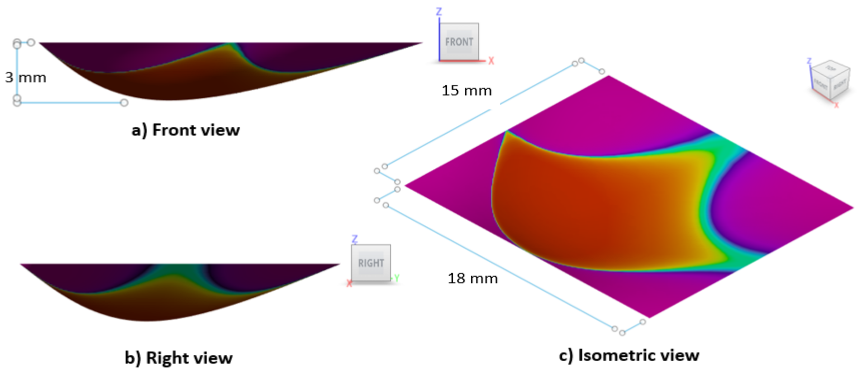
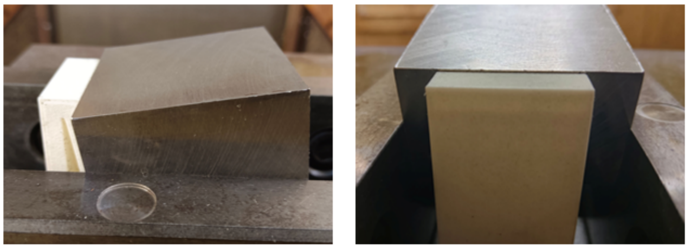


Figure 1. The 3D design of T-Spline curved surface a) Front view b) Right view c) Isometric view

In the present study, the asymmetric shallow concave surface of Stavax is developed using T-Spline technology adopted by Autodesk Fusion. The designer could freely sculpt any aesthetic shape on the surface using the manipulator's tool provided by the software based on T-Spline plane. The surface size of $18mm \times 15mm \times 3\ mm$ depth as shown in Figure 1 is matching with a Ø6 mm ball nose milling. The author limited the study to a shallow concave surface while maintaining T-Spline curvature form and aesthetic characteristics. The size of the radius of the ball nose directly affected the surface roughness during machining. Furthermore, the tool radius must be lower than the curvature of the surface to avoid overcuts and ensure the precision of the shape as per design.

CNC programmes based on scallop tool paths were generated using Autodesk Fusion for each TiAlN, TiSiN and AlTiN coating ball nose mill to evaluate the influence of the various coatings on tool performance. For each experiment running under flood coolant, the spindle speed was 3200 rpm, and the feed rate was 220 mm/min. The scallop toolpath was employed as a roughing and finishing strategy, leaving approximately 1.7 mm initially after roughing and 0.5 mm of a thin layer as stock to leave for the final finishing process. The strategy utilises a Ø6 mm carbide ball nose with an inclination angle of 10° to avoid ploughing in the contact area due to static rotation at the centre of the tools [15]. The stepover was consistently maintained at 0.2 mm throughout the experiments to achieve a good machined surface within a reasonable cycle time [16]. The same coated ball nose is fully utilised for the roughing and finishing process. The LiTZ CV800, a 3-axis universal CNC vertical milling machine with a Mitsubishi M70 CNC controller, was used to run the CNC programming on Stavax. An additively manufactured fixture with a 10° inclination was utilised to orient the workpiece during the 3-axis CNC milling process, as shown in Figure 2.

The Hitachi TM3030 tabletop scanning electron microscope (SEM) was used to evaluate the surface morphology of TiSiN, TiAlN, and AlTiN coatings. The comparative analysis of the tool surfaces was completed before and after the machining processes. Initial observations established a baseline for coating and flute uniformity. While post-machining observations focused on identifying wear mechanisms and surface degradation. This characterisation is essential for assessing the durability and performance of these coatings.



a) Front view b) Side view

Figure 2. Stavax setup on 10° inclination fixture

3. Results and Discussion

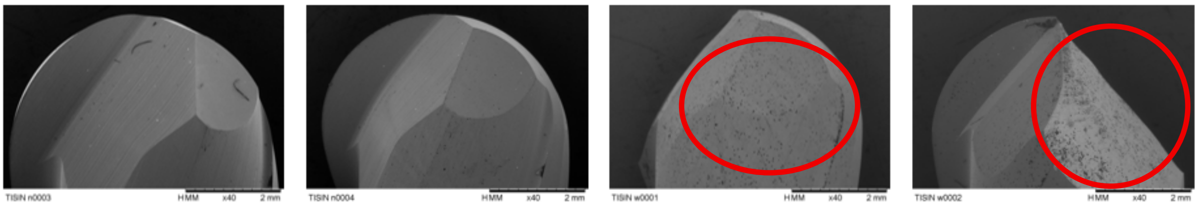
a) Machined Stavax b) TiAlN coated c) AlTiN coated d) TiSiN coated

Figure 3. The machined surface and the post-milling coated tools.

The physical appearance of TiAlN and AlTiN coatings of carbide ball noses after machining the curved surface shows no visible wear or failure. While under the same cutting parameters, the TiSiN-coated tool clearly exhibits flute breakage at the cutting edge. From the visual inspection of the TiSiN-coated tool, the broken cutting edge completely parted from the tool due to the failure of the carbide itself while shearing the workpiece, not from the TiSiN coating. The other cutting flute remains intact, showing no visible failure. Hence, during the contact of the TiSiN-coated cutting flute with the machined surface, the material can still be removed by the shearing process, creating chips [15]. Furthermore, the algorithm in Autodesk Fusion calculated the scallop tool path based on the effective radius of the cutting flute of the ball nose. As a result, the visual appearance of the machined surface presented no clear differences for all the concave pockets, as shown in Figure 3.

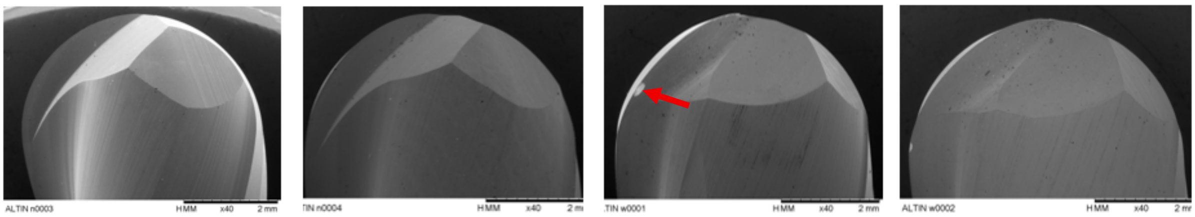
The surface of the 6 mm ball-nose end mills was analysed via SEM (x40 zoom) to evaluate the performance of AlTiN, TiAlN, and TiSiN coatings after machining Stavax ESR. Contrary to the theoretical high-hardness and advantages of nanocomposite structures, the TiSiN-coated tool presented the most severe degradation. The SEM images in Figure 4 clearly show catastrophic structural failure. The major fractured flute near the tooltip, exposing the underlying carbide substrate, suggests that the tool could not withstand the cyclic loads that existed in milling Stavax ESR.

In contrast to the TiSiN tool, the AlTiN and TiAlN coatings demonstrated more stable and predictable wear behaviour. The AlTiN coating showed moderate abrasive wear and localised micro-chipping (Figure 5 c). While less durable than TiAlN, it maintained its structural integrity without the catastrophic fracturing observed in the TiSiN sample. TiAlN in Figure 6 displayed the highest resistance to edge degradation. The wear was characterised by minor abrasive marks, with almost no delamination of coating.



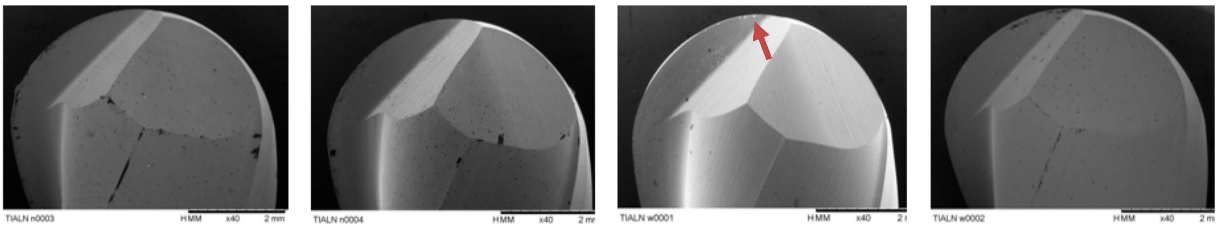
a) New TiSiN side i b) New TiSiN side ii c) Used TiSiN side i d) Used TiSiN side ii

Figure 4. SEM image of the 6 mm TiSiN-coated ball nose end mill: (a,b) initial condition of the new cutting edges, and (c,d) observed major edge degradation shown in the red circle after machining Stavax ESR.



a) New AlTiN side i b) New AlTiN side ii c) Used AlTiN side i d) Used AlTiN side ii

Figure 5. SEM image of the 6 mm AlTiN-coated ball nose end mill: (a,b) initial condition of the new cutting edges, and (c,d) observed moderate edge degradation shown by the red arrow after machining Stavax ESR.



a) New TiAlN side i b) New TiAlN side ii c) Used TiAlN side i d) Used TiAlN side ii

Figure 6. SEM image of the 6 mm TiAlN-coated ball nose end mill: (a,b) initial condition of the new cutting edges, and (c,d) observed minor degradation shown by the red arrow after machining Stavax ESR.

4. Conclusion and Future Research

The present study provided a valuable insight into the actual performance of commercial coated carbide ball-nose milling utilising commercial tools and equipment. From the study, the TiAlN-coated carbide ball nose exhibits the greatest durability during milling the shallow concave curve of Stavax ESR, followed by AlTiN-coated. Under the cyclic load stress, thanks to its great mechanical properties, the TiAlN-coated tool is able to maintain its structural integrity during machining the high-hardness metal. The lowest durability was observed in the TiSiN-coated sample, resulting from a severe fracture of the flute. Given the good structural integrity of TiAlN-coated tool, further studies should focus on optimising the cutting variables to minimise the secondary process of CNC milling in precision manufacturing.

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