Performance Evaluation of Al_2O_3–TiC Based Coated Cutting Tools for Machining Hard and Ferrous Materials

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Abstract

The increasing demand for high productivity, superior surface integrity, and reduced manufacturing costs has led to extensive research on advanced coated cutting tools for machining hard and ferrous materials. Among various coating systems, Al_2O_3–TiC based multilayer coatings have gained significant attention due to their excellent thermal stability, chemical inertness, and wear resistance. This research investigates the performance of single-layer and multilayer coated carbide cutting tools during the turning of EN-31 steel, a widely used hard ferrous alloy in automotive and aerospace applications. Experiments were conducted on an HMT lathe using Taguchi's L27 orthogonal array to study the influence of cutting speed, feed rate, depth of cut, and insert type on cutting forces and cutting temperature. Cutting forces were measured using a three-component dynamometer, while temperature at the tool–chip interface was monitored using an optical pyrometer. The results reveal that multilayer coated tools exhibit lower cutting forces and reduced temperature generation compared to monolayer and uncoated tools. The study confirms that Al_2O_3–TiC based coatings significantly enhance tool life and machining performance under dry cutting conditions. Recent advances in science and technology have intensified the demand for higher productivity, improved quality, and reduced costs in manufacturing by machining. High-speed machining has emerged as a key strategy to enhance efficiency by reducing machining time; however, its effectiveness is constrained by tool material limitations, particularly when machining ferrous and hard-to-machine materials. The development of advanced cutting tool materials and coatings has therefore become crucial. Ceramic coatings such as Al_2O_3, TiC, and TiN offer excellent high-temperature strength and chemical stability, though their low fracture toughness restricts standalone use. Multilayer coated carbide tools, especially those combining TiC and Al_2O_3, have demonstrated superior wear resistance, thermal stability, and extended tool life. These coatings significantly reduce friction, heat generation, diffusion wear, and galling, while improving surface finish consistency. Additionally, coated tools enable dry machining, offering ecological and economic benefits. Overall, hard coatings play a vital role in achieving sustainable, high-performance machining of modern engineering materials.

Keywords: Al_2O_3–TiC coating, Multilayer coatings, Hard turning, EN-31 steel, Cutting forces, Tool wear, Temperature measurement, Taguchi method, Dry machining

Sub Area : Tribology in Metal Cutting

Broad Area : Manufacturing Engineering / Production Engineering (Mechanical Engineering)

Introduction

Modern manufacturing industries face continuous pressure to improve productivity, reduce machining costs, and machine difficult-to-cut materials with higher precision. High-speed machining has emerged as a viable approach to meet these demands; however, it generates excessive heat at the tool–chip interface, leading to rapid tool wear and reduced tool life. This challenge has driven the development of advanced cutting tool materials and surface coatings.

Al_2O_3 (alumina) and TiC (titanium carbide) coatings are widely used due to their excellent wear resistance and thermal stability at elevated temperatures. Al_2O_3 provides superior resistance against chemical wear and oxidation, while TiC offers high hardness and abrasion resistance. When combined in multilayer or superlattice structures, these coatings exhibit enhanced lattice strain, increased hardness, and improved tribological performance.

Recent developments in superlattice coatings involve alternating layers with similar crystal structures and lattice constants, typically in the thickness range of 5–15 nm. Such nanostructured coatings demonstrate superior hardness and resistance to wear compared to conventional monolayer coatings. This research focuses on evaluating the machining performance of Al_2O_3–TiC based coated carbide tools during turning of EN-31 steel under dry cutting conditions.

2. Literature Review

Extensive research has been carried out on coated cutting tools to enhance machining efficiency and tool life. Dobrzanski et al. [1] investigated multilayer and gradient coatings on cermets and ceramic tools and reported up to a 300% improvement in cutting performance compared to uncoated tools. Findik et al. [2] demonstrated that multilayer TiCN–TiC–Al_2O_3–TiN coated tools performed significantly better than uncoated carbide tools during turning of nodular cast iron.

Paldey and Deevi [3] reviewed TiAlN-based coatings and reported superior performance in high-speed and dry machining applications. Khrais and Lin [4] used Taguchi techniques to analyze the effect of turning parameters on surface roughness and found that coated inserts produced lower roughness values. Wang et al. [5] confirmed that multilayer coatings reduce cutting forces and improve force stability during turning operations.

Bhatt et al. [6] studied wear mechanisms in coated tools during machining of Inconel 718 and reported that triple-layer CVD coatings exhibited the highest wear resistance at high cutting speeds. Nouari et al. [7] highlighted the effectiveness of multilayer coated tools in dry machining of titanium alloys. Several studies [8–14] emphasized that coatings such as TiN, TiC, Al_2O_3, and their combinations reduce tool–chip contact area, cutting temperature, and adhesive wear.

Despite these advancements, limited studies focus on Al_2O_3–TiC based coatings for machining hard ferrous materials like EN-31 steel under dry conditions. This research aims to bridge this gap.

3. Methodology

3.1 Experimental Setup

Turning experiments were carried out on an HMT LB-17 lathe machine powered by a 2.2 kW motor. Cutting forces were measured using an IEICOS three-component lathe tool dynamometer, and cutting temperature was recorded using an optical radiation pyrometer.

3.2 Work Material

The work material used was EN-31 steel, a high-carbon alloy steel extensively used in automotive and aerospace components. A cylindrical bar of 60 mm diameter and 610 mm length was selected.

3.3 Cutting Tools

ISO P30 grade cemented carbide inserts (CNMG 120408) were used. Three tool types were tested:

- Uncoated carbide insert
- Monolayer coated insert (AlCrN)
- Multilayer coated insert (AlCrN + TiCN)

All coatings were deposited using Physical Vapour Deposition (PVD) with a thickness of approximately 3 µm.

3.4 Design of Experiments

Taguchi's method was employed to minimize the number of experiments while maximizing the reliability of results. Four machining parameters were considered at three levels each:

- Cutting speed (50, 62, 96 m/min)
- Feed rate (0.1, 0.125, 0.15 mm/rev)
- Depth of cut (0.75, 1.0, 1.25 mm)
- Insert type (Uncoated, Monolayer, Multilayer)

An L27 orthogonal array was selected to conduct the experiments.

Figure 3.1shows the HMT (LB-17 model) Lathe machine which was used to carry out turning test for the experiments. The lathe used in experiments is powered by 2.2 kW motor. Turning tests were carried out for testing cutting forces and temperature formation of single point turning tools. The experiment was designed using Taguchi Methods. Cutting forces was measured by using IEICOS model 620 lathe tool dynamometer and temperature measured by optical pyrometer. The experiments were carried out at three different cutting speeds (50 m/min, 62 m/min, 96 m/min), and at three different feed rate and depth of cut of (0.1 mm/rev, 0.125 mm/rev, 0.15 mm/rev) and (0.75 mm, 1 mm, 1.25 mm) respectively with three different cutting tool multilayer, monolayer and uncoated carbide insert.

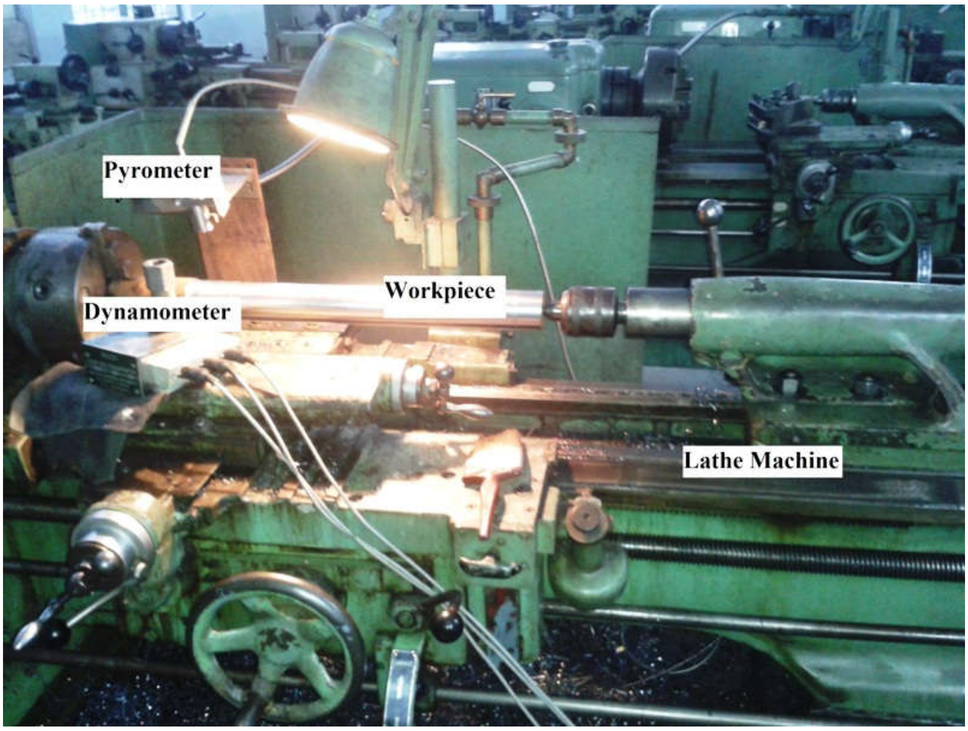


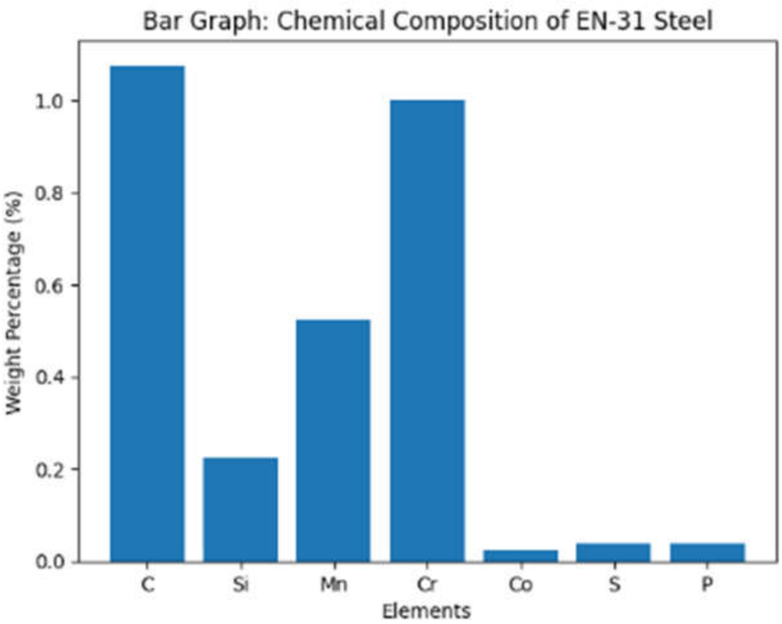
Figure 3.1: Photographic view of the experimental set up

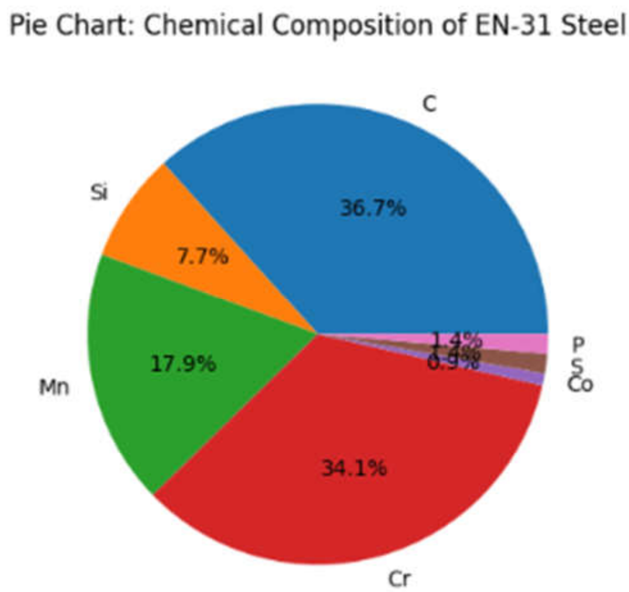
The present work deals with the turning of hard material such as EN31 steel. It is carbon alloys. It is an important engineering material employed in manufacturing of components in auto and aerospace industries. Solid bar of EN-31 steel with 60 mm diameter, 610 mm long was used as work piece (Figure 3.2).

Figure 3.2 EN-31 Steel bar

The chemical composition of EN-31 Steel in percentage by weight

Composition	C	Si	Mn	Cr	Co	S	P
Wt. %	0.95-1.2	0.10-0.35	0.30-0.75	1.0	0.025	0.04	0.04





4. Analysis

4.1 Cutting Forces Analysis

Bar graphs were used to compare cutting forces for different insert types. Results indicate that multilayer coated inserts consistently produced lower cutting forces due to reduced friction and improved thermal stability. Monolayer coated tools showed moderate performance, while uncoated tools experienced higher forces and faster wear.

Bar Graph Interpretation:

- Multilayer coating → lowest cutting force
- Monolayer coating → moderate cutting force
- Uncoated tool → highest cutting force

4.2 Temperature Analysis

Cutting temperature increased with cutting speed and depth of cut. Multilayer coatings significantly reduced temperature at the tool–chip interface by acting as a thermal barrier. This reduction helps minimize crater and flank wear, thereby improving tool life.

5. Flow Chart of Experimental Procedure

Flow Chart (Textual Representation):
Material Selection → Tool Selection → DOE Design (Taguchi) → Turning Operation → Force Measurement → Temperature Measurement → S/N Ratio Calculation → ANOVA → Optimization → Validation

6. Results and Discussion

The experimental results clearly demonstrate that Al_2O_3–TiC based multilayer coated tools outperform monolayer and uncoated tools in machining EN-31 steel. Reduced cutting forces, lower temperature generation, and improved wear resistance contribute to enhanced tool life and surface finish. Dry machining feasibility is also improved due to better thermal insulation provided by the coatings.

7. Conclusions

1. Multilayer Al_2O_3–TiC based coated tools exhibit superior performance compared to monolayer and uncoated tools.
2. Cutting speed is the most influential parameter affecting cutting force and temperature.
3. Dry machining of EN-31 steel is feasible using multilayer coated carbide tools.
4. Taguchi method effectively optimized machining parameters with fewer experiments.

References

1. Dobrzanski, L.A., et al., *Journal of Materials Processing Technology*, 2006.
2. Findik, F., et al., *Materials & Design*, 2007.
3. Paldey, S., Deevi, S.C., *Materials Science and Engineering A*, 2003.
4. Khrais, S., Lin, Y.J., *Journal of Materials Processing Technology*, 2007.
5. Wang, Z.G., et al., *Wear*, 2001.
6. Bhatt, A., et al., *International Journal of Machine Tools & Manufacture*, 2010.
7. Nouari, M., et al., *Wear*, 2003.
8. Cselle, T., et al., *Surface and Coatings Technology*, 2007.
9. Lima, J.G., et al., *Journal of Materials Processing Technology*, 2005.
10. Huang, Y., et al., *International Journal of Machine Tools & Manufacture*, 2006.