On-line wear characterization of TiN- and CrN-coated DIN115CrV3 steel for cutting tools application

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ABSTRACT

Purpose: This study compares the material removal performance of hardened steels DIN 115CrV3 coated with TiN and CrN using PVD method.

Design/methodology/approach: New on-line monitoring wear system, thermal imager, and weight loss method were used to analyze to quantify and compare with uncoated tools.

Findings: The results of abrasive wear experiments showed that weight loss increased with an increase in load applied for all tools. The microstructure and chemical analysis of each of the three tools showed some traces of abrasion and galling of Manganese from the workpiece. During abrasion test, thermal imager showed lower heating on the CrN coated tools. On-line wear analysis results show that at the low cutting speed (18 m/min), TiN-coated tools performed a higher wear resistance compared to rivals while at higher cutting speed CrN slightly show superior efficiency. The microstructure analysis of the tools confirmed fracture and galling on each of the tools.

Research limitations/implications: For future work, ceramic nano-coating on cutting tools can provide better wear resistance than ceramic micro coating.

Practical implications: Involve to use cheaper tools with higher mechanical properties. Usually, the cutting tools made from ceramic coating show an adequate level of wear resistance against the workpiece. Those tools, with the limited processing, can be used for machining soft steels.

Originality/value: New on-line method and thermal imager used in this study and for the first time DIN 115CrV3 was evaluated as cutting tools.

Keywords: Tool materials; Wear resistance; PVD coatings; Two-body abrasion; Steel

Reference to this paper should be given in the following way:
1. Introduction

The demand of cheaper tools with higher mechanical properties is increasing, depending on high specification. In the cutting operation, the selection of the appropriate cutting tools is essential to the improvement of surface quality, cost reduction, and dimensional and shape accuracy [11,13,19,23]. Coating materials and coating deposition technologies, such as plasma vapor deposition (PVD), have extended the application of coated tools such as hardened tool steel and high-speed steel-to-steel machining and stand out as an economical alternative to costly ultrahard tool materials such as carbide, ceramic, and cubic boron nitride CBN tools [1,3,4,6,7,21,22]. The performance of these tools largely depends on the physical properties and chemical compositions of coated tools and, especially, the characteristics of coating materials. Tool wear is a result of mechanical, thermal, chemical, and abrasive loads acting on the cutting edge. As the most common type of wear mechanism, abrasive wear occurs when hard particles move along a solid surface, thus creating resistance against them, and it is responsible for approximately 63% of the cost in all wear types. Most of the studies about the wear mechanisms of cutting tools have been conducted using steels of low to moderate hardness [12,17,18,20]. In the related literature, extensive research on the wear mechanism of cutting tools during machining of the workpiece was found, such as abrasion, adhesion, diffusion, and plastic deformation [2,8,10,14-16]. Recently, new methods are developed to assess the wear of cutting tools. For example, Çakan et al. (2010) devised an online method to monitor the cutting performance of AISI 1070 steel hardened at 760°C coated with a physical vapor deposition (PVD) method on DIN 9SMnPb36 as a workpiece [5]. Hard coatings, such as TiN, CrN, and so on, are the most used in cutting tools. Extensive researches are conducted on the wear properties of those coatings. Khlifi and Ben Cheikh (2013) assessed TiN, CrN, and AlCrN coatings on AISI 52000 steel. They found the lowest critical force of adhesion with TiN, whereas CrN coating had the highest after scratch tests [9]. DIN 115CrV3 steel is a low-alloy cold working tool steel that has sufficient strength and ductility. This alloy is used to produce machine tools such as spiral and tap drills, broaching tools, and metal saws in the industries. In this work, it will be evaluated as a cutting tool for the first time. The objective of this study was to develop new cheaper tools with higher wear resistance. For this purpose, the wear behavior and associated wear mechanisms of the cutting tools; uncoated, coated with TiN and CrN DIN 115CrV3 steel used against DIN 11SMn30 steel specimens under dry turning operation conditions. Both microscopic and microstructural aspects of tool wear were taken into consideration as abrasive wear, and machining tests of cutting tools were conducted under varying cutting speeds at a constant feed rate of 0.06 mm/rev and a cut depth of 0.8 mm. Scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) analyses were applied to observe worn tool surfaces, wear products, and wear mechanisms.

2. Materials and methods

Rod bar with a diameter of 40 mm and a length of 300 mm of DIN 115CrV3 steel was machined to shape cutting tools (10×10×100 mm). After hardening at 780°C and tempering at 180°C with a heat treatment, the surfaces of the cutting tools were cleaned before the cathodic arc PVD method was used to produce TiN- and CrN-coated tools. Figure 1 shows the SEM images of CrN- and TiN-coated tools. TiN and CrN had an average coating thickness of 4.72 and 2.19 µm, respectively. TiN coating had double thickness compare with CrN. In addition, both coatings show a good adherence to substrate without porosity and cracks.

![Cross-sectional view of a) TiN and b) CrN coatings](image-url)
2.1. Abrasive wear tests

The experiment was carried out using a turning machine (AT 280) with a shaft diameter of 105 mm and a length of 1400 mm. The abrasive or the counter body used during the test was DIN 11SMn30 steel. Before and after abrasion, the initial and the final weights of the samples were taken using a weighing scale of $10^{-4}$ g sensitivity. The abrasive wear experiments were carried out at the loads of 10, 20, 30, and 40 N. For each experiment, the speed of machining steel was held constant at 25 m/min and the wear rate at 0.628 m/s. The experiments were stopped once in 100 m for weighing until the end of the experiment (1000 m). Wear tests were repeated three times on different surfaces of the same samples for the calculation of means. In addition, thermal imager Testo 882 was used to imaging the temperature variation on the both surface cutting tools and workpiece.

2.2. Online monitoring method

The cutting performance of the cutting tools produced was investigated with an online monitoring system that consists of one laser diode, a photodiode, and a computer for acquiring data, as described by Çakan et al. (Çakan, 2011). The machining test was performed at the three cutting speeds of 18, 25, and 35 m/min with a constant feed rate of 0.06 mm/rev and a cut depth of 0.8 mm.

3. Results and discussions

3.1. Weight loss of cutting tools

The cutting tools hardened by heat treatment and coated using the PVD were tested for weight loss. Figure 2 shows the wear behavior of hardened steel, TiN-coated cutting tools, and CrN-coated cutting tools at the different loads depending on the distance. Weight loss increased with an increase in load applied for each cutting tools. As can be seen from Figure 2a, when the load applied was 10 N, the hardened steel had the highest weight loss followed by the ceramic coatings. These weight diminutions after 1000 m of abrasion were approximately 0.0019 g for hardened steel, 0.0015 g for CrN-coated tools, and 0.0012 g for TiN-coated tools. By increasing the applied loads to 20 N, the wear intensity progressed rapidly at the beginning of the experiment until 300 m, decreased gradually up to 600 m, and then accelerated again until the end of the experiment (Figure 2b). The same behavior was observed for the 30 N applied load (Figure 2c). It can be stated here that the diminution of weight loss is due to adhesion wear instead of abrasive wear, especially after 300 m. At the highest applied load (40 N), the abrasion is more severe than the previous load, and the wear had the same behavior as 10 N applied load.

Fig. 2. Weight loss depending on distance with an applied load: a) 10 N, b) 20 N, c) 30 N, and d) 40 N
In general, the hardened steel of tools had a higher wear than the TiN- and CrN-coated ones. This may be due to the brittle martensitic phase in the hardened steel, which broke continuously and generated particles. The lowest wear was obtained with the ceramic-coated tools; the TiN coating led to slightly lower weight loss than the rival CrN coating under abrasive wear because of its higher hardness.

The images of SEM and energy-dispersive spectroscopy (EDS) of tools after 20 N of applied load are presented in Figure 3 and Table 1. Because of too many images and similar results, the SEM and EDS analyses for 10, 30, and 40 N were not presented in this study. At first glance, the adhesion of some particles was observed on the wear region of TiN-coated tools (Figure 3a). The EDS analysis of the wear region, shown beside the small quantity of the main material of the coating, Ti element, and Mn element, is presented in Table 1. In addition, the quantity of Fe and C elements increased in the wear region compared with the untreated zone. The possible explanation of the presence of Mn in the wear region is that it comes from the workpiece. On the other hand, the rise of elements can be explained by the rupture of coating during wear.

![SEM images and EDS analysis of hardened steel cutting tools after 20 N of abrasive wear](image)

**Fig. 3.** SEM images and EDS analysis of hardened steel cutting tools after 20 N of abrasive wear (50×): a) TiN-coated tools and b) CrN-coated tool

| Table 1. EDS analysis of hardened steel, TiN-coated tools, and CrN-coated tools after 20 N of abrasive wear |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **TiN-Coated Tools** | **Area** | **C Kα** | **Fe Kα** | **Mn Kα** | **Ti Kα** | **N Kα** |
| | | **Weight, %** | **Atom, %** | **Weight, %** | **Atom, %** | **Weight, %** | **Atom, %** | **Weight, %** | **Atom, %** |
| Untreated | 3.74 | 10.75 | 8.64 | 5.43 | — | — | 76.34 | 56.03 | 11.28 | 27.79 |
| Wear | 5.14 | 20.91 | 88.4 | 78.47 | 0.35 | 0.31 | 0.29 | 0.30 | — | — |
| **CrN-Coated Tools** | **Area** | **C Kα** | **Fe Kα** | **Mn Kα** | **Cr Kα** | **N Kα** |
| | | **Weight, %** | **Atom, %** | **Weight, %** | **Atom, %** | **Weight, %** | **Atom, %** | **Weight, %** | **Atom, %** | **Weight, %** | **Atom, %** |
| Untreated | 3.18 | 8.38 | — | — | — | — | 77.01 | 46.85 | 19.81 | 44.77 |
| Wear | 3.64 | 14.61 | 77.12 | 67.58 | 0.19 | 0.16 | 19.05 | 17.65 | — | — |
| **Hardened Steel Tools** | **Area** | **C Kα** | **Fe Kα** | **Mn Kα** | **Cr Kα** |
| | | **Weight, %** | **Atom, %** | **Weight, %** | **Atom, %** | **Weight, %** | **Atom, %** | **Weight, %** | **Atom, %** |
| Untreated | 7.72 | 27.7 | 91.63 | 71.76 | — | — | 0.65 | 0.54 |
| Wear | 8.98 | 31.13 | 90.52 | 68.45 | 0.32 | 0.28 | 0.18 | 0.14 |
The wear zone analysis of CrN-coated tools figure out that the adhesion of particles is unclear, and fine traces of abrasive wear were noted (Figure 3b). The quantitative analysis confirmed that the decrease of Cr elements and the increase of Fe and C elements explain the breaking of the CrN coating (Table 1). The presence of Mn elements in the analysis confirms some adhesion of wear particles. Compared with TiN-coated tools, CrN-coated tools had lower adhesion wear and were located at some place on the surface instead of all surfaces as TiN-coated tools. The thermal imaging of the tools taken during experiment of weight loss shows the temperature distribution on the both surface cutting tools and workpiece (Figure 4). It is obvious that CrN coated tools had lower warm than rivals and hardened steel tools had higher temperature distribution on the surface.

![Fig. 4. Thermal imaging of tools during weight loss test at 1 min and 3 min](image)

### 3.2. Online analysis of wear behaviour

The online abrasive wear during the machining of the workpiece with the cutting tools is presented in Figure 5. For each of the three cutting tools, there was a sudden increase in voltage at the beginning of the experiment (initially observed peaks), and then regular intervals of voltage variation were observed.

The test was carried out with an 18 m/min cutting speed, and the constant feed rate of 0.062 rpm revealed that the TiN-coated cutting tools had better wear resistance than rival tools (Figure 5a). The SEM images of the cutting tools taken at the end of the experiment showed that the hardened tools and TiN-coated cutting tools had a slight rupture and fracture, whereas the CrN-coated cutting tools had severe rupture, fracture, and adhesion on the tip (Figure 6). Increasing the cutting speed to 25 m/min rendered peaks slightly more acute (Figure 5b).

![Fig. 5. Voltage variation of tools at different cutting speed: a) 18 m/min, b) 25 m/min and c) 35 m/min](chart)

At the beginning, the fall of the voltage became steady, and then the peaks were severe until the end. These peaks indicate microfractures of the cutting tools. The SEM analysis at Figure 7 confirmed CrN-coated tools had a small microfracture, whereas the TiN-coated tools and hardened steel had a large microfracture and adhesion on the tip. TiN-coated cutting tools behaved slightly worse than the CrN-coated ones but better than the hardened steel ones. The cutting tools were subjected to a maximum...
cutting speed of 35 m/min, and the intensity of peaks or voltage variation was found to be higher than before (Figure 5c). This behavior probably increased the surface roughness of the workpiece relative to the other cutting speeds tested. For the hardened steel, the initial voltage suddenly decreased because of microcracks, and wear reached the highest level, although it was not observed in the ceramic coating. CrN-coated cutting tools were microcracks and galling, and the TiN-coated and hardened steel ones had crater-type fractures with microfractures (Figure 8).

As was observed in this study, damage to the cutting tools started with wear, continued with plastic deformation, and ended up with fracture. When compared with Çakan et al. (2008), (Çakan et al., 2008) our results showed that the CrN-coated cutting tools had a slightly better wear resistance than the TiN-coated cutting tools at the higher cutting speeds.

Fig. 6. Abrasive wear of cutting tools after an 18 m/min cutting speed: a) hardened steel, b) TiN-coated tools and c) CrN-coated tools

Fig. 7. Abrasive wear of cutting tools after a 25 m/min cutting speed: a) hardened steel, b) TiN-coated tools and c) CrN-coated tools

Fig. 8. Abrasive wear of cutting tools after a 35 m/min cutting speed: a) hardened steel, b) TiN-coated tools and c) CrN-coated tools
4. Conclusions

The wear properties of tools made of DIN 115CrV3 steel coated with TiN and CrN were evaluated during the cutting of smooth material DIN 115Mn30. The coated tools performed better wear resistance than hardened steel tools. In particular, TiN-coated tools had better abrasive wear resistance and flank wear at low cutting speed, whereas CrN-coated tools outperformed them at medium and higher cutting speed. The weight loss confirmed that at low and high load, wear was higher, and both mechanisms (abrasive and adhesive wear) were observed on the tools. These mechanisms were also observed after cutting on the tip of tools, including fracture. Usually, the cutting tools made of ceramic coating perform an adequate level of wear resistance against the workpiece. Those tools with the limited processing can be used for machining soft steels.

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