

# Wear Mechanism of Multilayer AlCrWN/AlCrWSiN-coatings on Cemented Carbide Tools Prepared by Arc Ion Plating in Dry Cutting of Hardened Sintered Steel

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**Abstract.** In this study, to clarify the wear mechanism of the multilayer AlCrWN/AlCrWSiN-coated tool in cutting of hardened sintered steel, the rate of wear in the cutting of hardened sintered steel using three types of coated tools was investigated. The Type I tool had a single layer (Al60, Cr25, W15)N coating film, the Type II tool had a single layer (Al53, Cr23, W14, Si10)N coating film and the Type III tool had a multilayer (Al60, Cr25, W15)N/(Al53, Cr23, W14, Si10)N-coating film. Scanning electron microscope (SEM) observation and electron dispersive X-ray spectrometry (EDS) mapping analysis of the abraded surface of the coating film were performed. The following results were obtained: 1) The wear rate of the Type III tool was the slowest. 2) The area of the worn surface on the rake face "S" and the contact length between the rake face and the chip "D" were measured. Comparing the three types of coated tools, both the "S" and the "D" of Type I tool were the smallest, and those of Type II tool were the largest. 3) The main wear mechanism of Type II and Type III tool showed abrasive wear. However, the main wear mechanism of the Type I tool was both abrasive wear and adhesion wear. 4) The critical scratch load of the Type I tool, 81 N, was lower than that of the Type II or the Type III tool, over 130 N. Therefore, comparing the Type I and Type III tools, due to the wear mechanism of the Type I tool being both abrasive wear and adhesion wear, the wear rate of the Type I tool, which has the lower critical scratch load, was slower.

## 1 Introduction

Comparing the performances of the AlCrN coated tool and TiN coated tool, the AlCrN coated tool can increase the depth of cut by about 33% [1]. Furthermore due to the better heat resistance of the AlCrN coating film, the tool life of the end mill with the AlCrN coating is longer than that with the TiAlN coating [2-3]. However, our study results show that the critical scratch load of the AlCrN coating film, which is the value measured by the scratch test, is 77 N and the micro-hardness is 2760 HV<sub>0.25 N</sub>. Therefore, in order to improve both the critical scratch load and micro-hardness of the AlCrN coating film, a cathode material of the Al-Cr-W target with tungsten (W) added to the cathode material of the Al-Cr target was used [4]. The Al-Cr-W based coating film has both high hardness and excellent critical scratch load and can be used sufficiently as a coating film of WC-Co cemented carbide cutting tools [4]. Furthermore, the friction between the face of the cutting tool and the chip decreases when W is added [5-6].

The addition of Si to the TiN coating film converts the [111] -oriented columnar structure to a dense fine grain structure.

Thin films of Ti-Si-N have been deposited by physical vapor deposition to improve the wear resistance

of TiN coatings [7]. Cutting experiments showed that the TiAlSiN coated end mill with a Si content of 4.78 atom% had the least flank wear and improved its milling distance by about 20% over the TiAlN coated end mill [8]. Furthermore, at a temperature of 700°C or lower, the hardness of the AlCrWSiN film is higher than the hardness of AlCrN [9]. The addition of Si leads to the refinement of crystal grains and greatly influences the phase composition and mechanical properties due to its formation. Amorphous Si<sub>3</sub>N<sub>4</sub> [10-11]. Many multilayer coating films have been developed to improve tool life [12-16].

The rate of wear of the AlCrWN/AlCrWSiN-coated tool, which has the multilayer coating system, was slower than that of the single layer AlCrWSiN coated tool in the cutting of hardened steel at a feed rate of 0.2 mm/rev [17]. In addition, the tool wear of the AlCrWN/AlCrWSiN-coated tool, which has the multilayer coating system, was investigated in the cutting of hardened sintered steel. [18]. Furthermore, the properties of the multilayer AlCrWN/AlCrWSiN-coating film were also clarified [18]. However, the wear mechanism of the multilayer AlCrWN/AlCrWSiN-coated tool has not been clarified in the cutting of hardened sintered steel.

In this study, to clarify the wear mechanism of the multilayer AlCrWN/AlCrWSiN-coated tool in the cutting

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of hardened sintered steel, the rate of wear in the cutting of hardened sintered steel using three types of coated tools was investigated. The Type I tool had a single layer (Al60, Cr25, W15)N coating film, the Type II tool had a single layer (Al53, Cr23, W14, Si10)N coating film and the Type III tool had a multilayer (Al60, Cr25, W15)N/(Al53, Cr23, W14, Si10) N-coating film. SEM observation and EDS mapping analysis of the abraded surface of the coating film were performed.

## 2 Experimental procedure

Hardened sintered steel was used for the work-piece. Table 1 shows the chemical composition and properties of the work-piece. The thickness, hardness and scratch strength (critical scratch load measured by a scratch tester) of various coating films formed on the surface of the substrate, which was a WC-Co cemented carbide ISO K10 by the arc ion plating process, were measured. Coating deposition was performed by an arc ion plating system (KOBEL STEEL, LTD. AIP-S40).

Table 2 shows the tool material in turning of the work-piece. Namely, the Type I tool, which has the (Al60, Cr25, W15)N coating film and the Type II tool, which has the (Al53, Cr23, W14, Si10)N coating film, are mono-layer coating systems. The Type III tool, which has both the (Al60, Cr25, W15)N coating film and the (Al53, Cr23, W14, Si10)N coating film, is a multilayer coating system.

The configurations of tool inserts were ISO TNGA160408. The insert was attached to a tool holder MTGNR2525M16. The lathe used was a precision lathe (Type ST5, SHOUN MACHINE TOOL Co., Ltd.) by adding a variable-speed drive. The driving power of this lathe is 7.5/11kW and the maximum rotational speed is 2500 min<sup>-1</sup>. The work-piece was turned under the cutting conditions shown in Table 3, and the tool wear was investigated.

**Table 1.** Chemical composition and properties of sintered steel.

Chemical composition [mass %]				
C	Cu	Ni	Mo	Fe
0.3 - 0.7	1 - 2	3 - 5	0.2 - 0.8	Bal.
Properties				
Hardness: 339 HBS (5 mm/ 7350 N)		Density: 7.1 Mg/m <sup>3</sup>		

**Table 2.** Tool material in turning of hardened sintered steel.

Tool	Coating layer(s)
Type I tool *	(Al60, Cr25, W15)N
Type II tool *	(Al53, Cr23, W14, Si10)N
Type III tool **	Substrate → (Al60, Cr25, W15)N → (Al53, Cr23, W14, Si10)N → (Al60, Cr25, W15) N → (Al53, Cr23, W14, Si10)N →……

Substrate: Cemented carbide ISO K10

\*: Mono-layer coating system, \*\*: Multilayer coating system

**Table 3.** Cutting conditions.

Cutting speed (Vc)	1.67 m/s
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Feed speed (f)	0.2 mm/rev
Depth of cut (ap)	0.1 mm
Cutting method	Dry cutting method

## 3 Results and discussion

In the cutting of hardened sintered steel, the tool wear of the three types of coated tools was investigated. Figure 1 shows the tool wear at a cutting speed of 1.67 m/s, feed rate of 0.2 mm/rev and cutting depth of 0.1 mm. In the case of all coated tools, a slight crater was found on the rake face. Remarkable adhesion of the work-piece was not observed on both the rake face and the flank face, and remarkable flaking of the coating layer was not observed as shown in Figure 1. As will be described later, adhesion of the work-piece was observed on the coating layer of the Type I tool.

The above results indicate that the main tool failure of all coated tools was the flank wear up to the cutting distance where the maximum value of the flank wear width is about 0.2 mm. Therefore, the maximum value of the flank wear width (VBmax) was measured under a microscope.

Figure 2 shows the cutting distance versus flank wear width in turning hardened sintered steel with various coated cemented carbide tools at a cutting speed of 1.67 m/s, feed rate of 0.2 mm/rev and depth of cut of 0.1 mm. In this figure, the data of the wear rate of Type III was quoted from reference number [18]. As Figure 2 shows, (1) comparing Type I and Type II, which are mono-layer coating systems, the wear rate of Type I is slower than that of Type II. (2) The wear rate of Type III, that has the multilayer coating system, is slower than that of Type I or Type II.

Therefore, it is effective to make the AlCrWN coating film and the AlCrWSiN coating film into a layered form in order to improve the wear resistance.

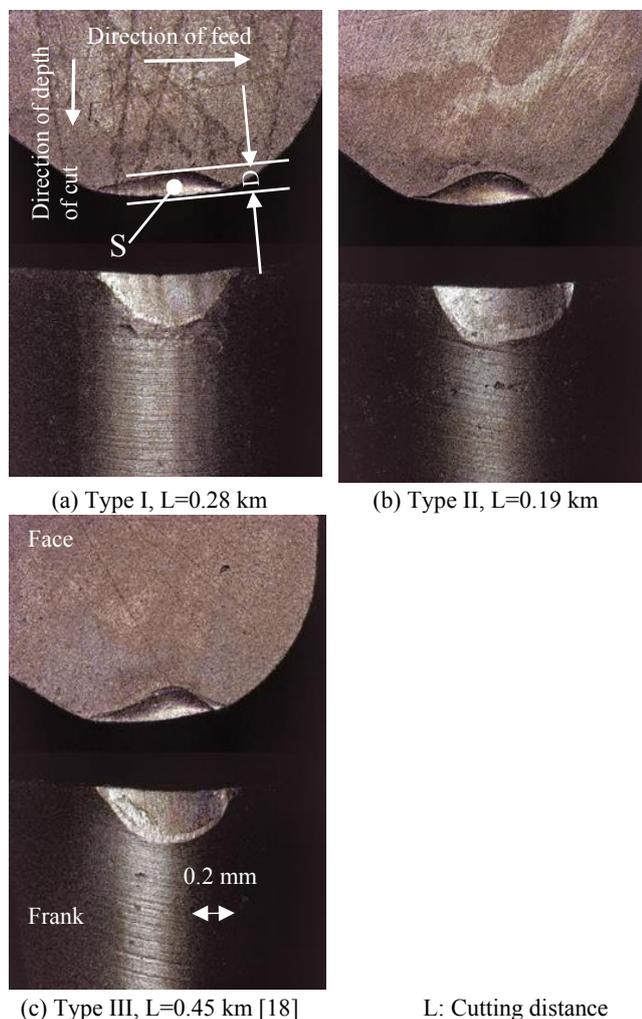
Therefore, in order to clarify why the layered form is effective, the contact state of the tool and the chip on the rake face were investigated. Table 4 shows the “S” and the “D” shown in Figure 1(a). In Table 4, the “S” is the area of the worn surface on the rake face, and “D” is the contact length between the rake face and the chip shown in Figure 1(a). Comparing the Type I and Type II tools, both the “S” and the “D” of the Type I tool are smaller than that of the Type II tool. The contact area between the rake face and the chip of the Type I tool is smaller than that of the Type II tool. Therefore, it is considered that in the case of the cutting of hardened sintered steel by the Type I tool, due to the friction force between the rake face and the chip being small, the cutting temperature is lower and the wear rate is slower.

Comparing the Type I and Type III tools, both the “S” and the “D” of the Type III tool are larger than that of the Type I tool. The contact area between the rake face and the chip of the Type III tool is larger than that of the Type I tool. Therefore, in the case of the cutting of hardened sintered steel by the Type III tool, the cutting temperature becomes higher than that of the Type I tool. However, the wear rate of the Type III tool is slower than that of the Type I tool as shown in Figure 2.

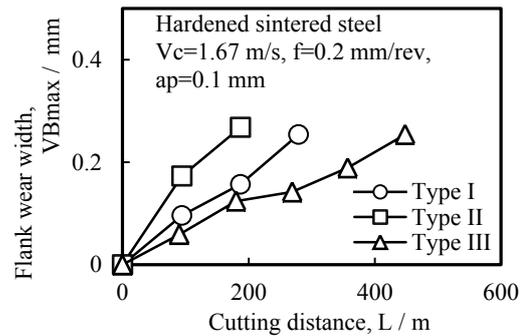
So, in order to explain the effectiveness of the multilayer coating film, SEM and (EDS) observation were performed on the worn surface.

Figure 3(a) and (b) show the EDS mapping analysis on the abraded surface of the Type I and III tool, respectively. The elements analyzed are oxygen (O), nitrogen (N) and iron (Fe). Fe is the main chemical component of the hardened sintered steel. Comparing the oxygen, nitrogen and iron elements on the abraded surface of all types of coated tools, there is little difference in the mapping of oxygen, nitrogen and iron elements. Therefore, the excellence of the multilayer coating film cannot be clarified just by elemental analysis of the worn surface of the cutting part.

Next, detailed observations were conducted on part "A" and part "B" shown in Figure 3. The parts "A" and "B" are the worn surface on the coating layers. Figure 4 shows the SEM observation and the EDS mapping analysis on the worn surface details of "A" and "B" shown in Figure 3. In Figure 4(a), regions (I), (II) and (III) are the abraded surface of the substrate, abraded surface of the coating film and surface of the coating film, respectively. Figures (i) and (ii) show the details of "A" and "B" presented in Figure 3, respectively.



**Figure 1.** Tool wear observed after turning sintered steel with three types of coated tools at a cutting speed of 1.67 m/s, feed rate of 0.2 mm/rev and cutting depth of 0.1 mm.



**Figure 2.** Cutting distance versus flank wear width in turning hardened sintered steel with various coated cemented carbide tools at a cutting speed of 1.67 m/s, feed rate of 0.2 mm/rev and depth of cut of 0.1 mm.

**Table 4.** "S" and "D".

Tool type	S [ $\times 10^{-3}$ mm <sup>2</sup> ]	D [mm]
Type I	47.9	0.124
Type II	55.0	0.152
Type III	49.1	0.140

S: Area of worn surface on the rake face shown in Fig. 1(a)

D: Contact length between the rake face and the chip shown in Fig. 1(a)

The SEM and the EDS observation results of the three types of coated tools were compared as shown in Figure 4 (i). Comparing the SEM observation of the three types of coated tools as shown in Figure 4(i), there are many striate lines scratched by hard materials on the abraded surface in the case of all types of coating layers. Furthermore, in the case of Type I shown in Figure (i)(a), adhesion of the work-piece is observed on the abraded surface of the coating film in the area indicated by the ellipse.

In the case of the details of "B" shown in Figure 3, the figure of which is shown in Figure 4(ii), the same result as that shown in Figure 4(i) is presented. That is, in the case of Type I shown in Figure (ii)(a), adhesion of the work-piece is observed on the coating layer in the area indicated by the ellipse, too. There is no noticeable difference in the mapping state of the iron element in the case of all types, too.

Therefore, the wear mechanism of Type I is both abrasive wear and adhesion wear. And the main wear mechanism of Type III is abrasive wear.

For abrasive wear, the wear-resistance of the coating film often depends on the hardness of the coating film. Table 5 shows the characteristics of coating films. Although the thickness of the coating film of the Type III coating film, 2.5  $\mu\text{m}$ , is thinner than that of the Type I coating film, 4.4  $\mu\text{m}$ , the wear rate of the Type III tool was slower than that of the Type I tool as shown in Figure 2. As compared with the critical scratch load of the Type I and Type III tools, the critical scratch load of Type III, over 130 N, is higher than that of Type I, 81 N. The micro-hardness of Type III, 3000 HV<sub>0.25N</sub>, is slightly lower than that of the Type I, 3110 HV<sub>0.25N</sub>. Thus, there is not much difference in the hardness of the two types of coating films.

Therefore, comparing the Type I and Type III tools, due to the wear mechanism of the Type I tool being both abrasive wear and adhesion wear, the wear rate of the Type I tool, which has the lower critical scratch load, was slower.

**Table 5.** Characteristics of coating films.

Cutting tool	Thickness of coating film [μm]	Micro-hardness [HV <sub>0.25N</sub> ]	Critical scratch load* [N]
Type I [19]	4.4	3110	81
Type III [18]	2.5	3000	>130

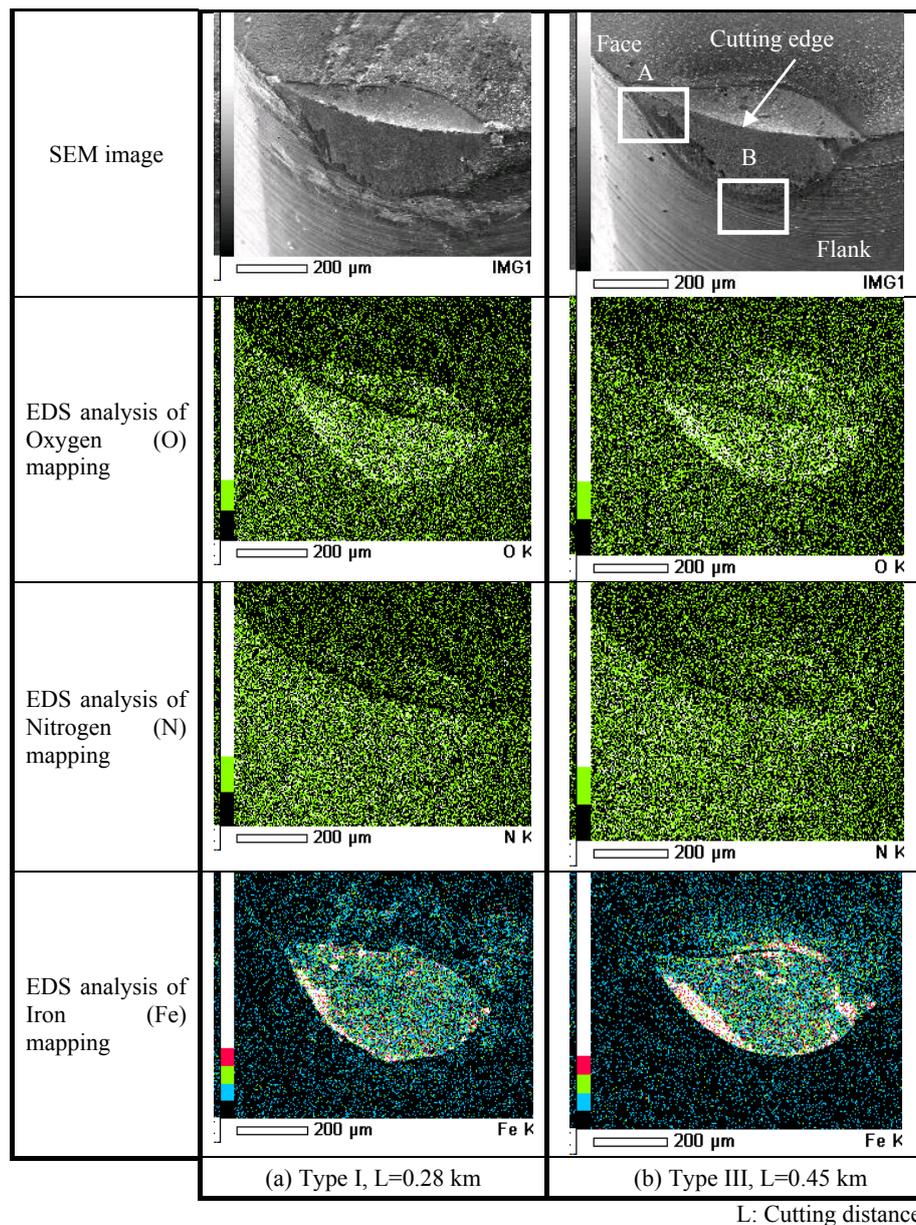
\*: Measured value by scratch test

### 4 Conclusion

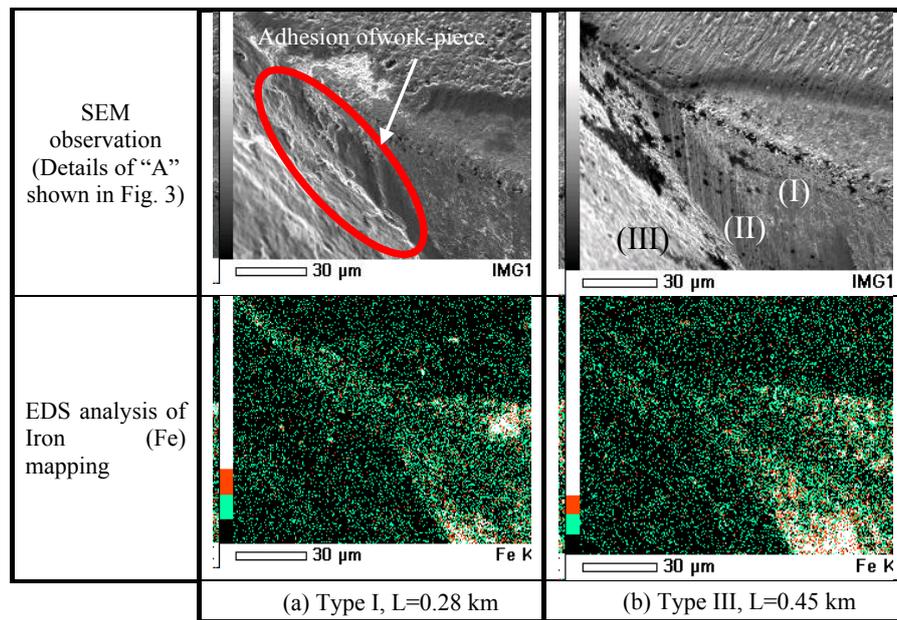
In this study, SEM observation and EDS mapping analysis of the abraded surface of the coating film were performed in order to clarify the wear mechanism of the AlCrWN/AlCrWSiN-coating film in the cutting of hardened sintered steel. The Type I tool had a single layer (Al60, Cr25, W15)N coating film, the Type II tool had a single layer (Al53, Cr23, W14, Si10)N coating film and the Type III tool had a multilayer (Al60, Cr25, W15)N/(Al53, Cr23, W14, Si10) N-coating film.

The following results were obtained:

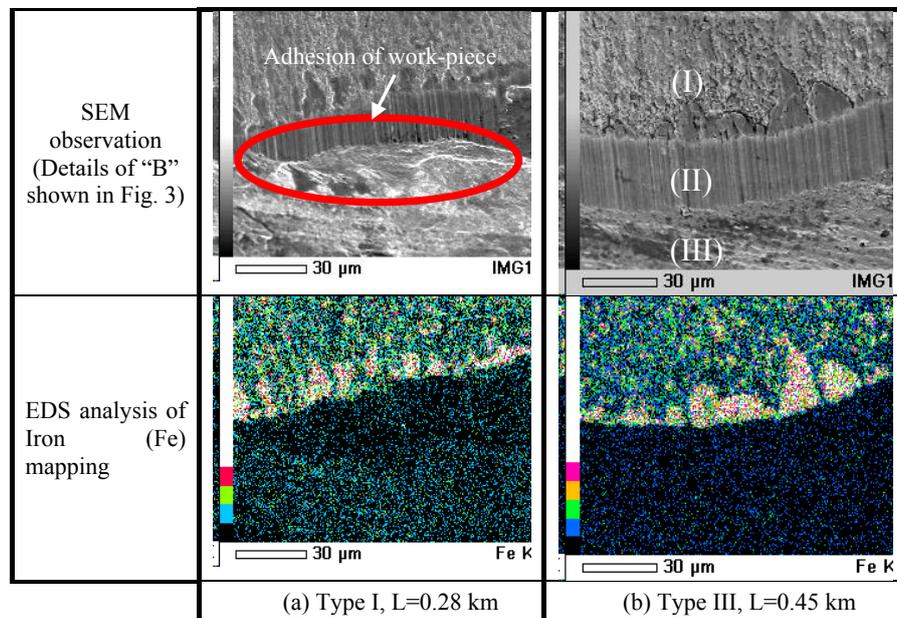
- 1) The wear rate of the Type III tool was the slowest.



**Figure 3.** SEM observation and EDS mapping analysis on the abraded surface of the Type I and Type III coated tool.



(i) Details of "A" shown in Fig. 3



(ii) Details of "B" shown in Fig. 3

(I): Abraded surface of substrate, (II): Abraded surface of coating film, (III): Surface of coating film, L: Cutting distance

**Figure 4.** SEM observation and EDS mapping analysis on the worn surface details of "A" and "B" shown in Fig. 3.

2) The area of the worn surface on the rake face "S" and the contact length between the rake face and the chip "D" were measured. Comparing the three types of coated tools, both the "S" and the "D" of the Type I tool were the smallest, and those of the Type II tool were the largest.

3) The main wear mechanism of the Type II and the Type III tool was abrasive wear. However, the main wear mechanism of the Type I tool was both abrasive wear and adhesion wear.

4) The critical scratch load of the Type I tool, 81 N, was lower than that of the Type II or the Type III tool, over 130 N.

Therefore, comparing the Type I and Type III tools, due to the wear mechanism of the Type I tool being both

abrasive wear and adhesion wear, the wear rate of the Type I tool, which has the lower critical scratch load, was slower.

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