# Innovative Methods for the Investigation of Tool-Chip Adhesion and Layer Formation during Machining

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**Abstract**
Tool-chip and tool-work adhesion often limit machinability, but quantitative methods to characterise adhesion are absent. Hence, a methodology based on interrupted turning was used and layer formation was quantified using a number of techniques. This included surface topography studies using 3D white light interferometry, element mapping and profiling using SEM-EDS and Laser ablation time of flight mass spectrometry (LA -TOFMS) along with temperature mapping using IR-CCD. Results from turning tests with stainless steel 316L indicate clearly that the above techniques compliment each other and provide valuable new insight on contact friction, adhesion and layer formation.

**Keywords**:
Machining, Steel, Tool-chip adhesion

## 1 INTRODUCTION

Understanding the tool-chip contact phenomenon in terms of prevailing friction, adhesion and tribo-chemical interactions is of central importance to the science of metal cutting. Tool performance as well as the quality of the machined product are affected by adhesion. Lack of quantitative information on metal cutting friction is also a serious limitation in the application of commercial or other models for simulation of metal cutting [1]. Adhesion is especially critical in the case of materials like stainless, other high alloyed steels and super alloys. But even in the case of common austenitic stainless steels only such features as chip formation [2], work hardening mechanisms [3] and the role of inclusion treatment [4-6] have been relatively well documented. Information regarding friction conditions and adhesion at tool-chip contact in quantitative terms [7] is very meagre.

Methods such as Raman spectroscopy [8] and SIMS [9] have been attempted for tool-chip contact analysis, but often the weakness had been in the lack of complimentary quantitative information to describe the situation as a whole since both thermomechanical and metallurgical state of the contact are required. This is the motive for the present investigation. Accordingly, a methodology incorporating both the effects of time and temperature level was developed through the use of interrupted turning test. Tool-chip adhesion and layer formation was quantified using a number of techniques, namely 3D White light interferometry for quantifying adhesion through the layer of reaction products, SEM-EDS-WDS to describe the metallurgical state, Laser mass spectrometry (LA-TOFMS) to identify the chemical species and combining these with experimental information about the contact temperature distribution (IR-CCD) and stress levels.

## 2 MATERIAL, TOOL AND METAL CUTTING TESTS

Austenitic steel grade AISI 316L was selected in the present investigation. The material was supplied in the form of hot rolled bars and subjected to Calcium treatment for machinability enhancement purpose.

Coated cemented carbide inserts (ISO M25) with geometry SCMW120408 were used. The CVD-coating consisted of three layers of TiN, $Al_2O_3$ and Ti(C,N) deposited on cemented carbide substrate. The total coating thickness was 5.5 µm and insert edge radius was ~35 µm. To follow the progress of tool-chip adhesion with contact time, longitudinal interrupted turning tests at different cutting speeds (vc=160,220 and 320 m/min) were carried out using a modern CNC lathe. Feed rate (f =0.15 mm/rev.) and depth of cut (ap =2 mm) were kept constant. Tool-chip contact time from 20 s to 248 s was achieved by interrupted turning, resulting in different machined lengths L (=12, 55, 165, 330, 660 m).

The tools were subsequently examined using different techniques for quantifying adhesion on rake surface as a function of time and cutting conditions.

## 3 QUANTIFICATION OF TOOL-CHIP ADHESION

### 3.1 Adhering layer thickness from 3D-white light interferometry measurement

The application of white light interferometry in metal cutting is relatively new and the method was employed in recent studies for quantifying crater wear in cutting tools [10,11]. However in the present study, a Wyko®1000 white light interferometer was used to map the thickness of the adhesion products on the rake. An area of about 1mm$^2$ on rake surface was scanned as shown in Figure 1 displaying a typical 3D-topography map obtained on the coated tool insert after 4 minutes of machining (L=660m) at vc=160 m/min. This clearly indicates the presence of a layer of work material adhering on rake surface. Figure 2 illustrates the development of the adhering layer with increasing machined length (i.e. contact time).

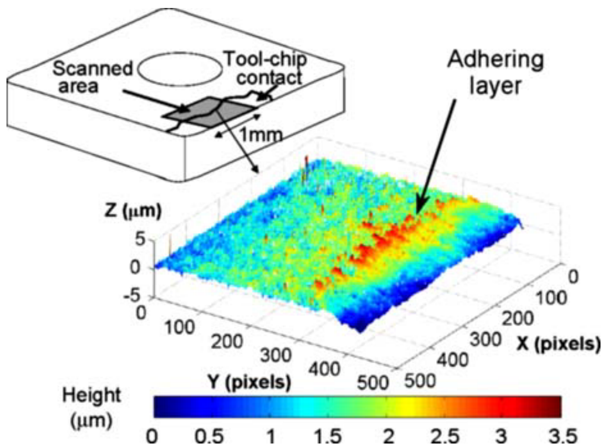


Figure 1: Results from 3D white light interferometry showing varying adhering layer of work material (vc=160m/min, L=660m).

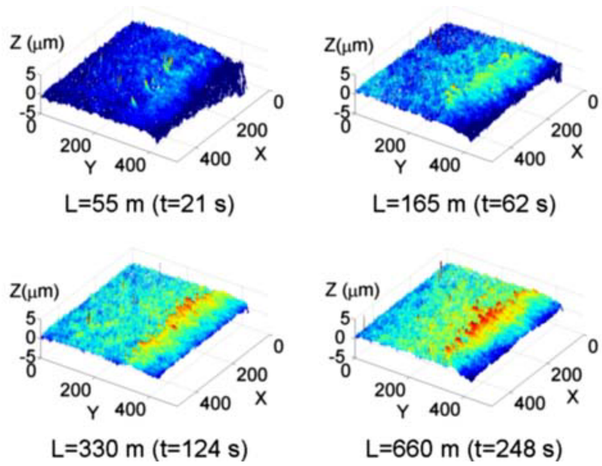


Figure 2: Progressive build-up of adhering layer for different machined lengths (vc=160 m/min).

The transverse and longitudinal sections from such 3D maps (respectively y and x in Figure 1) could be used to quantify the thickness of the adhering layer on rake surface. Results in Figure 3 show that as machined length increases from 12 to 660 m, the thickness of adhering layer increases from 1-1.5 µm to 2.5-3 µm in the region of tool-chip contact. The effect of cutting speed (hence temperature) is also noticeable (Figure 3) as the layer is thickest at vc=220 m/min.

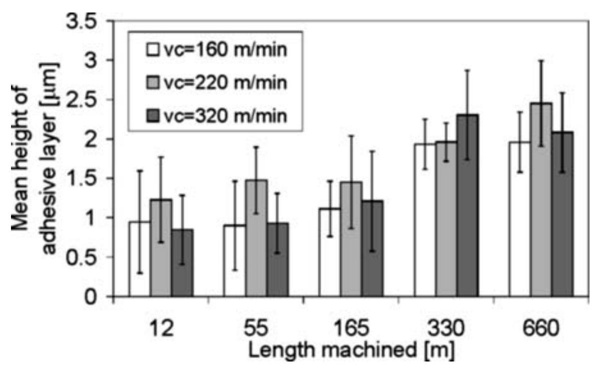


Figure 3: Effect of cutting speed and machined length on the height of adhering layer.

### 3.2 Element mapping using SEM-EDS-WDS

The coated inserts were examined in scanning electron microscope (SEM) using the back-scattered electron imaging mode (BSE). Quantitative element mapping of tool-chip contact area was done using Energy dispersive spectrometry (EDS). Wavelength dispersive spectrometry (WDS) was also used for point analysis when some elements could not be separated with EDS (ex. S and Mo).

Three distinct regions could be identified on the BSE picture from rake surface in Figure 4: (a)-close to tool tip: zone whith little adhesion where only small apserities of work material are present; (b)-mid-contact length: region of tool-chip interfacial sliding; (c)-second half of tool chip contact: thick adhering layer of work material appearing in white.

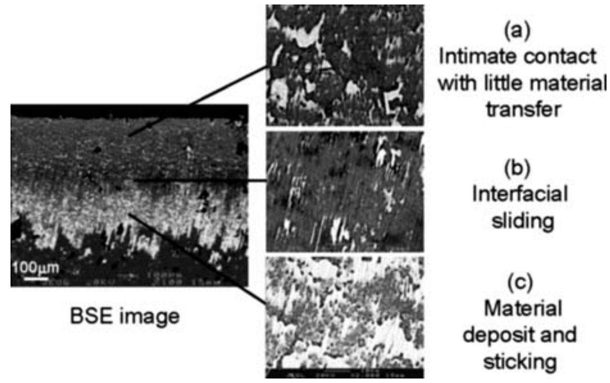


Figure 4: SEM-BSE observation of tool rake surface (vc=160 m/min, L=330m).

SEM-EDS element mapping of tool rake surface enabled us to identify the elements present in the regions (a), (b) and (c) such as in Figure 4. Results are displayed in Figure 5 where the abundance of specific elements is shown in white. Region (a) close to tool tip consisted essentially of Ti corresponding to the outer coating layer (TiN). In the mid-contact length region (b), Al and O from $Al_2O_3$ intermediate coating layer were present. Traces of Ca and Si were also found in region (b), indicating the presence of a selective transfer of inclusion layer, most likely ($CaO$-$Al_2O_3$-$SiO_2$). Finally in zone (c), Fe and other alloy elements (Cr, Ni, Mn and Mo) were present confirming work material layer deposit in this region.

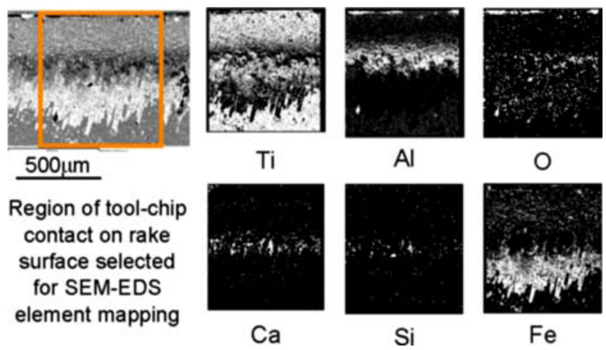


Figure 5: SEM-EDS element mapping of tool chip contact area (vc= 160m/min, L=660 m).

The findings regarding the inclusion layer in zone (b) were also confirmed by the element profiles obtained from SEM-EDS analysis along the contact length as shown in Figure 6. WDS analysis coupled with EDS was also performed in zone (b) and the comparatively low amount of sulphur and manganese detected in this region (Table 1) did not reveal any evidence of manganese sulphide inclusion (MnS).

| O | Al | Si | Ca | S | Mn |
|---|---|---|---|---|---|
| 35.00 | 9.41 | 1.52 | 4.02 | 0.07 | 0.03 |

Table 1: WDS-EDS analysis (w%) of zone b in Figure 4.