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Experimental and theoretical studies on stainless steel transfer onto a TiN-coated cutting tool

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Abstract

Stainless steel is a good example of a metal that is not easily machined. To explain such behavior an understanding of the fundamental adhesion between the workpiece and the tool is invaluable. It is a well-known fact that build-up layers form in the interface, but little attention has been given to the very first layer that adheres to the tool surface. Although this layer rapidly becomes covered by successive material transfer, this layer and its ability to stick to the tool surface control the successive material transfer and influence the cutting properties. In this work, a quick stop test is employed to interrupt the cutting of a 316L stainless steel using a TiN-coated cemented carbide cutting insert. Different analytical techniques, such as transmission electron microscopy, X-ray photoelectron spectroscopy and scanning electron microscopy, as well as theoretical atomistic modeling, were used to study the early adhesion.

Keywords: Stainless steel; Metal cutting; Adhesion; Electron microscopy; First-principle electron theory

1. Introduction

Machining of austenitic stainless steel is generally considered to be difficult, in part because of its high plasticity and its tendency to work harden. Depending on the cutting parameters, the composition of the stainless steel workpiece and the tool surface, different transfer layers may build up on the tool surface. Such layers may be desired or even formed deliberately with the purpose of protecting the cutting tool from wear or reducing the cutting forces [1,2]. However, they may also be unintentional and undesired, triggering the formation of built-up edges and causing degradation of the surface quality of the machined component [1]. There are a number of models in the literature trying to explain the chip–tool interactions and the build-up of such layers (e.g., Refs. [1,3–7]). Most models nowadays assume a stagnant, seized layer at the coating surface as proposed by Trent [1].

Modern tools are coated with a ceramic coatings, providing lower affinity to steel and lower thermal conductivity of the tool, which increases the chip temperature and facilitates flow of the chip. However, cutting with coated tools also involves material transfer and build-up of stagnant layers on the tool surface. Katayama and Hashimura showed that the extent of Fe transfer to the tool could be reduced by the use of different ceramic coatings when cutting low-carbon steels [8]. However, the same study did not prove complete elimination thereof.

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An understanding of the factors that influence the build-up of transfer layers is valuable from both manufacturing and modeling perspectives. In recent years, various methods have been used to study transfer layers on metal cutting tools in terms of both chemistry and microstructure. Most often, such studies have been performed after extensive use of the tool when relatively thick layers of transferred material have developed [2,9–11]. Very few studies concern the initially transferred material, which is unambiguously the fundamental step in the build-up process.

Quick stop tests which separate the tool from the chip by abruptly reversing the relative motion between the tool and the workpiece can provide valuable information on the adhesion between transfer layers and the tool surface. As described by Trent, when after such experiments part of the tool remains adhered to the chip or vice versa, strong bonds between the chip and the tool must have been present which had caused seizure to occur. The absence of such remnants does not disprove seizure, a stagnant transferred layer or strong bonds, but merely shows that the interfacial bonds were weaker than the cohesion of the tool and the workpiece material at the time of separation.

This work focuses on the early build-up of transferred material in the secondary shear zone when cutting stainless steel. A quick stop mechanism is used to interrupt the cutting of a 316L stainless steel workpiece with a TiN-coated cutting tool after only a short time of cutting. The surfaces of the chip and the tool are examined using high-resolution microscopy to determine where the separation occurred. Moreover, first principles theoretical calculations based on density functional theory, a method that has proven to be a good approach for describing chemical interactions at interfaces [12–14], are used to study the interaction between the work material and the tool. This allows prediction of the likely location of the separation, which is compared with the experimental results.

2. Experimental

2.1. Materials

The tool used was a cemented carbide insert (WC + 10 wt.% Co, hardness 1600 HV_{3kg}) with a TiN coating deposited using reactive arc evaporation. The hardness of the coating was 24 GPa and the roughness on its surface was measured to R_a 0.16 μm.

The work material was 316L stainless steel hot-rolled bar machined into a “hollow” cylinder, with an outer diameter of 160 mm and an inner diameter of 154 mm. Cutting from the side of the cylinder, the width of the cut was 3 mm.

2.2. Methods

The tool was mounted in a tool holder capable of pivoting around the tool holder base. Initially, the tool holder was fixed using shear pins and cutting commenced at a speed of 150 m min^{-1} and a feed rate of 0.15 mm rev^{-1}. After about 2 s of cutting, an explosive gun was used to interrupt the process instantly by breaking the shear pins and thus removing the tool holder and the tool from the workpiece in a pivotal movement.

To model the interaction between the work material and the TiN coating theoretically, the Projector Augmented Wave (PAW) method [15], as implemented in the VASP program [16], based on density functional theory was applied. The exchange–correlation function was calculated within the generalized gradient approximation (GGA), using the Perdew–Wang parameterization [17]. $3p^63d^2\ 4s^2$(Ti), $2s^22p^3$(N) and $3d^64s^2$(Fe) valence orbitals and 875 eV cutoff energy were applied. The calculated TiN/face-centred cubic (fcc) Fe interface structures contained five TiN and nine Fe layers separated by 5 Å of vacuum. Three layers of TiN and six layers of Fe were relaxed in the calculations. For a unit cell with 20 Ti, 20 N and 72 Fe atoms, a grid of $2 \times 4 \times 1$ k-points was used. Non-magnetic calculations were performed at zero temperature. DFT-based methods are known to provide reliable surface energies for metals [18,19] and compounds [13,14].

A section of the workpiece close to the cutting zone, with part of the recently formed chip still attached, was cut free. The surface of this and the cutting insert were examined by scanning electron microscopy (SEM), and samples were extracted using focused ion beam (FIB) for studies by transmission electron microscopy (TEM). Different regions on the tool surface were examined using cross-sectional TEM (FEI Tecnai F30 ST), energy dispersive electron spectroscopy (EDS) (EDAX on a Leo 440), SEM (Leo 1550) and X-ray photoelectron spectroscopy (XPS) (Physical Electronics Quantum 2000) in the attempt to determine the occurrence and amount of steel transfer to the tool during cutting. TEM samples were extracted perpendicular to the chip flow direction. The region of interest for TEM sample preparation was located in a FEI Strata DB235 dual beam FIB/SEM and subsequently, a thin lamella was fabricated using FIB. Prior to ion bombardment, the region of interest was coated by electron and subsequently ion beam deposited Pt. The existence of a thin Fe surface layer was probed by SEM/EDS analysis, where the surface sensitivity was enhanced using a low acceleration voltage of 7 kV.

3. Results and discussion

3.1. Analysis of separated surfaces

On a polished and etched cross-section, the microstructure of the austenitic work material, the severe deformation in the primary shear zone and the stagnant layer under the chip can be clearly seen in Fig. 1.

Areas with different characteristics can be seen on the surface of the chip that was in contact with the tool at the time of disengagement. Close to the cutting zone (see Fig. 2a), flakes of coating and tool material are stuck in the chip. This proves an adhesion between the coating and chip strong enough to cause cohesive fracture within