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Adhesion phenomena in the secondary shear zone in turning of austenitic stainless steel and carbon steel

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ABSTRACT

This paper aims to increase the understanding of the adhesion between chip and tool rake face by studying the initial material transfer to the tool during orthogonal machining at 150 m/min. Two types of work material were tested, an austenitic stainless steel, 316L, and a carbon steel, UHB 11. The tools used were cemented carbide inserts coated with hard ceramic coatings. Two different CVD coatings, TiN and Al_2O_3, produced with two different surface roughnesses, polished and rough, were tested. The influences of both tool surface topography and chemistry on the adhesion phenomena in the secondary shear zone were thus evaluated. Extensive surface analyses of the inserts after cutting were made using techniques such as Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), X-ray Photoelectron Spectroscopy (XPS), and Transmission Electron Microscopy (TEM). As expected, cutting in the stainless steel resulted in a higher amount of adhered material, compared to cutting in the carbon steel. Remnants of built-up layers were found on the surfaces of the 316L chips but not on the UHB 11 chips. Moreover, it was shown that for both materials the tool roughness had a profound effect, with the rougher surfaces comprising much higher amounts of adhered material than the polished ones. Non-metallic inclusions from both types of workpiece steels accumulate in the high temperature area on the inserts. The general tendency was that higher amounts of transferred material were found on the TiN coating than on the Al_2O_3 coating after cutting.

1. Introduction

The adhesion properties between work material and tool material in the secondary shear zone are of significant importance both regarding the energy spent in the cutting process and the performance of the cutting process itself. Although these properties have been studied for many years, and significant new knowledge has been gained on the subject, the details of the processes are still neither fully understood nor exploited in tool design.

Austenitic stainless steels are generally known to be more demanding to machine than plain carbon steels. The austenitic stainless steel adheres strongly to the tool and chips often remain stuck to the tool after cutting. A high tendency to work harden, together with a low thermal conductivity compared to plain carbon steels, cause a high temperature in the flow-zone, which promotes more extensive chip–tool interactions. The temperature distribution on the tool rake face has, however, the same character as when cutting other steels, i.e. a comparatively cool region at the cutting edge and a temperature maximum some distance from the cutting edge, as described by Trent and Wright (2000). Adding oxide forming elements such as Ca, or other elements such as S, to stainless steels have been shown to improve their machinability. Fang and Zhang (1996) described the role of Ca in a turning tests with a TiC carbide tool cutting in calcium deoxidised free cutting stainless steel (Ca content < 0.01% and S content ≤ 0.1%). It was shown that an adhered layer was formed on the tool surface by the extrusion of non-metallic inclusions in the steel. The layer consisted mainly of (CaO, MgO, MnO)–Al_2O_3–SiO_2 and grew thicker with cutting length and increased cutting speed. The formation process of the layer was summarized as "viscous and extruding, adhering and coating, hardening and thickening, and then relatively stable". After becoming stable, it was assumed to protect the tool from abrasive, adhesive and diffusive wear, and to lower the temperature in the flow zone.

There are a number of models of the chip–tool contact, and the majority nowadays assumes a stagnant seized layer at the tool–chip interface, with more or less full contact between chip and tool

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material, as proposed by Trent and Wright (2000). Qi and Mills (1996) proposed a new dynamic flow zone model based on the concept of a “cutting interface”. This interface is not located at the normal interface where the speed of the chip is zero, but some distance into the chip, where the maximum shear strain rate of the chip is found. This dynamic model was proposed to explain the formation of transfer layers at the tool–chip interface and was applied in a case study of three different austenitic stainless steels; a calcium deoxidised free cutting austenitic stainless steel (Ca < 0.01% and S ≤ 0.1%), a resulphurized austenitic stainless steel (0.17% S), and an ordinary austenitic stainless steel. An adhered layer, containing high concentrations of Al, Ca, Si, and S, was found on the WC–TiC–Co tool after machining the calcium deoxidised stainless steel while a MnS layer adhered to the tool when turning in the resulphurized stainless steel. When machining the ordinary stainless steel, a layer of work material was generated on the tool surface. The layer formed by the calcium deoxidised steel was stable also at higher cutting speeds and offered protection from adhesive, diffusive and abrasive tool wear. The MnS layer formed by the resulphurized stainless steel was found to be viscous and thin at higher cutting speeds, implying that the “cutting interface” was located at the tool surface which accelerated the abrasive and diffusive wear. It did, however, prevent welding and seizure of workpiece material onto the tool which reduce the adhesive wear. The easily sheared layer could also act as a solid lubricant, reducing friction force and cutting temperatures. In contrast, the work material adhering to the tool when machining the ordinary stainless steel suggested risks of severe adhesive wear.

Katayama and Hashimura (1995) studied the interfacial adhesion between different cutting tool materials and free-cutting low carbon steels. They found that the frictional forces measured during cutting were connected to the amount and type of adhered materials, Fe and/or MnS, found on the tool surface. The tool material was shown to influence the adherence of elements and hence the measured friction force. Little attention was, however, given to the surface finish of the tools.

Wiklund et al. (2012) studied the initial material transfer of austenitic stainless steel onto a TiN coated cutting tool by performing quick-stop tests, freezing the chip forming process, after only a short cutting distance. Three different zones were identified when studying the tool and chip after the quick-stop. Close to the cutting zone, tool fragments were found sticking to the chip. This implied very strong adhesive forces between tool and chip in this zone during cutting. This zone was followed by a stagnant zone further away from the cutting zone where no signs of relative movement between chip and tool surface was found. The adhesion between the tool and the chip was weaker than the cohesion of both the tool and the chip material, allowing the separation after quick-stop to occur at the tool–chip interface. Despite this, indications of an extremely thin layer of adhered steel remaining on the TiN surface were found. The third and final contact zone, furthest away from the cutting zone, was described as a region with only temporary contact between the chip and the tool. An abundance of transferred steel, initiated at protrusions in the coating surface and thereafter successively built-up, was found in this region.

Klocke and Krieg (1999) stated that physical vapour deposition (PVD) and chemical vapour deposition (CVD) are the two most relevant groups of deposition processes for cutting tools. In different forms their dominance prevails, as illustrated by, e.g. Dobrzański and Pakuła (2005) and Soković et al. (2009). Coatings manufactured by CVD are often used for high-speed metal cutting where there is a high demand of wear resistance, as described by, e.g. Bouzakis et al. (2012), while PVD coatings are suitable for applications with demands on edge-line toughness such as milling, as exemplified in, e.g. the industrial survey on gear cutting tools by Gerth et al. (2011). In general, PVD coatings are thinner than coatings applied by CVD. The CVD technique is commonly employed since it is the only deposition method that allows economical large-scale production of high quality alumina coatings as discussed by Ruppi (2005). From this reasons, choosing two CVD tool coatings for this study is motivated.

Moreover, the CVD tool coatings TiN and Al_2O_3 are both frequently used in industrial machining of steels and they are both known to have high wear resistance as described by Holmberg and Matthews (1994) and in studied detail by, e.g. Dearnley (1985). Compared to TiN, Al_2O_3 is thermally stable, shown by Trinh et al. (2009), has a lower thermal conductivity at high temperatures, as shown by Cahill et al. (1998) and a lower solubility in steel at high temperatures, which limits the chemical wear as described by Dearnley, (1985). All this suggest it is the more suitable coating in applications where very high temperatures are involved. Another aspect which could influence the wear characteristics of the coating is the material transfer to the tool rake face. This paper reports on several aspects of the adhesion between the chip and the rake face of the tool by studying the initial material transfer during orthogonal machining of two different work materials. Two very different kinds of steels were used; a commercial machinability-improved grade of the austenitic stainless steel 316L and a plain carbon steel, UHB 11. These were chosen to represent challenging materials, 316L, and steels characterized by a good machinability, UHB 11. The influence of the surface roughness of the tool on the initial material transfer, which has often been neglected in earlier works, was also studied.

2. Experimental procedure

2.1. Experimental set-up

Cutting tests were performed in a lathe with a setup shown in Fig. 1. The workpiece consisted of a hollow cylinder with an inner diameter of 154 mm and an outer diameter of 160 mm, resulting in a wall thickness of 3 mm. By cutting from the side of the cylinder (longitudinal turning), the width of cut became equal to the wall thickness. The cutting speed was 150 m/min and the feed rate was 0.154 mm/rev. The cutting and feed forces were measured using a KISTLER 3-component dynamometer (type 9257A). This sensor has a maximum range of 10 kN in the z direction (sensitivity −3.5 pC/N) and 5 kN in the x and y directions (sensitivity −7.5 pC/N). The rake and clearance angles were 0° and 11°, respectively. Rapid engagement and disengagement of the tool, with the workpiece rotating at full speed, was used. Data from the force measurements proved this method to be capable of controlling the tests durations at an accuracy of about 0.1 s. Tests with two different durations were executed, 1 s and 5 s, and all tests were repeated twice.

2.2. Materials

The tools tested were cemented carbide inserts (SPUN 120308, WC + 10.5 wt% Co, hardness 1350 HV_{3kg}) with two different CVD coatings. The coatings were composed of approximately 3 μm Ti(C,N) as an inner layer, and 3 μm of either TiN or α-Al_2O_3 as a top layer. The inner Ti(C,N) layer was deposited onto the substrates at a temperature of 885 °C using $TiCl_4$ as Ti precursor reacting with a gas mixture of CH_3CN:H_2:N_2. The TiN top layer was deposited at 1010 °C using $TiCl_4$ as Ti-precursor reacting with a gas mixture of H_2:N_2, while the α-Al_2O_3 top layer was deposited at 1010 °C using $AlCl_3$ as Al precursor reacting with a gas mixture of CO_2:H_2S:H_2. The depositions were performed in a Bernex 325 reactor.

Coated inserts with two different surface topographies were prepared. One referred to as “standard rough” where the blanks