Available online at www.sciencedirect.com
SCIENCE DIRECT®
International Journal of Machine Tools & Manufacture 45 (2005) 211–218
INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE DESIGN, RESEARCH AND APPLICATION
www.elsevier.com/locate/ijmactool

An experimental investigation of work material microstructure effects on white layer formation in PCBN hard turning

G. Poulachon[a,*], A. Albert[a,1], M. Schluraff[a,1], I.S. Jawahir[b,2]

[a]ENSAM, LaBoMaP, Rue Porte de Paris, Cluny 71250, France
[b]University of Kentucky, Lexington, KY 40506-0108, USA

Received 23 October 2003; accepted 22 July 2004
Available online 23 September 2004

Abstract

White layers formed in machining of hardened alloys are known to be very hard and resistant to standard etchants used in metallographic studies. Many studies have been performed on this subject, but only with little progress showing definite results concerning the actual effectiveness of white layer formation. Hence, the basic question that remains unanswered is: are the white layers a tribological advantage for the manufacturing industry producing parts/components from hard alloys? The focus of this study is to investigate the evolution of white layers produced during progressive tool flank wear in dry hard turning with CBN (cubic boron nitride) tools, and to correlate this with the surface integrity of the machined surface. The following four materials were machined: X160CrMoV12 cold work steel (AISI D2), X38CrMoV5 hot work steel (AISI H11), 35NiCrMo16 high toughness steel and 100Cr6 bearing steel (AISI 52100). Samples of chips were metallographically processed and observed under an electronic microscope to determine whether white layers are present or not. More specifically, chip-forms/shapes were studied to determine how they developed during machining with potential appearance of white layers, with a view to correlating the chip-forms/shapes with the white layer formation. Finally, by using scanning electron microscopy and EDS techniques on these chip samples, properties and microstructures of white layers were deduced in order to verify some of the prevalent theories.

Keywords: White layer; Hard turning; Microstructure; Chip-forms; Surface integrity

1. Introduction

The lack of knowledge concerning surface quality and integrity of the machined surfaces, especially with the appearance of white layers, in hard turning, has severely limited the study of the effectiveness of white layers in machining of parts/components such as bearing rolls, pinions. In this study, the appearance of white layers and the associated effects of cutting parameters at varying tool-wear rates have been studied and compared for various work materials commonly used in industry. The results clearly show that the thickness of these layers depends on the nature of the microstructure of the work material. The experience obtained during this study involving the white layer formation in various work materials also allows a special procedure to coat the chip specimen with a nickel coating in order to take care of the polishing direction, thus avoiding the usual damage and possible breakage of the white layers.

In a finish turning, surface quality and integrity are often of great concern because of their impact on product performance in terms of functional behavior and dimensional stability. It has been shown that these factors can also be used as a tool-changing criterion. Thus, the understanding of how the appearance of white layers is related to tool-wear and cutting parameter variations affecting surface quality and integrity, is of practical significance.

* Corresponding author. Tel.: +33-3-8589-5330; fax: +33-3-8559-5370.
E-mail addresses: gerard.poulachon@cluny.ensam.fr (G. Poulachon), aurelie.albert@gadz.org (A. Albert), muriel.schluraff@gadz.org (M. Schluraff), jawahir@engr.uky.edu (I.S. Jawahir).
[1] Tel.: +33-3-8589-5330.
[2] Tel.: +1-859-257-6262; fax: +1-859-257-1071.

0890-6955/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmachtools.2004.07.009

2. State-of-the-art on white layer formation in hard machining

White layer is a result of micro-structural alteration on a martensite structure. It is called 'white' because it appears white under an optical microscope or featureless in a scanning electron microscopy (SEM).

White layers can be found in many material removal processes such as turning, reaming, grinding and electrical discharge machining. The generation of a white layer and its quantification would indicate the amount of surface energy brought into the part/component. Currently, three different theories are prevalent to explain the structure of white layer formation. According to Barry and Byrne [1] and Chou and Evans [2], the high austenite content of the surface white layer clearly confirms the occurrence of the reverse martensite transformation during machining. A rapid increase in temperature, combined with high pressure generated by the action of the tool, transforms the machined surface to the austenitic state. When the tool leaves, the surface cools down and the critical speed of martensite formation is reached by convection of heat into the air and by conduction into the workpiece material. As a result of the high speed, (Chou and Evans [2] have estimated the surface cooling rate in hard turning to be of the order of 10^4 °C/s), some austenite has no time to transform and some retained austenite traces can be found in the surface layer. Mybokwere et al. [3], Cho et al. [4] and Zhang et al. [5] show that dynamic recovery is the dominant process in the formation of surface white layers and internal white adiabatic shear bands, which are internal non-etching white bands in steels, deformed at high strain rates (from 10^3 to 10^6 s^{-1}). Dynamic recovery can be explained simply as the beginning of dislocations, arranged in cell boundaries. Assisted by the local increase in temperature, due to rapid localized deformation, dislocations concentrate into tangles, producing regions of high and low dislocation density and forming sub-grain boundaries. A new hypothesis has been developed by Zurecki et al. [6]. It is postulated that there is an almost complete dissolution of carbides due to the high temperature generated by plastic deformation. The more the amount of carbon in the matrix increases, the more the melting point of the steel decreases. As the tool leaves the material, the white layer cools down quickly which induces freezing of its microstructure. A small quantity of non-quenched martensite or retained austenite may develop within the white layer.

There are several problems concerning the white layers' microstructure, and two major theories have been proposed. The white layer microstructure is recognized as an 'abnormal martensite' composed of nanocrystalline, partially transformed material with a high density of dislocations considered to be a very fine martensite lath (misoriented cells between 30 and 100 nm) with fine dispersed carbides and high rate of retained austenite. According to Tönshoff et al. [7], retained austenite is the major composition of white layer structure. Also, Tönshoff [7] and Chou and Evans [2] show that the volume fraction of retained austenite in white layers increases threefold compared to the one in virgin work material. However, more experiments are needed to confirm it. Indeed, the authors of this paper found no publications correlating the retained austenite to grain size. The microstructural evolution during white layer formation appears to be unknown. Matsumoto et al. [8] claim that the white layer has a mixed martensite α' and austenite γ structure. Indeed, martensite in steels is a metastable structure. Moderate heat will lead to its decomposition to cementite and ferrite, in a tempering process. The machined surface encounters an extremely short cycle thermo-mechanical process. With such a high heating rate such as over 10^6 °C/s, as shown by Chou and Evans [2], if the austenite transformation starting temperature is reached, martensite could transform into austensite by reverse martensitic transformation. In the subsequent rapid cooling stage (once the machined surface leaves the tool flank contact), austenite can transform back into martensite, if the starting martensite transformation temperature is reached.

In order to understand the mechanics of the revolution of white layers, it is important and necessary to know the effects of various process factors. Some studies have been performed to determine the effect of tool-wear, cutting speed and hardness on white layer depth. Results of those experiments are summarized below. Chou and Evans [2] investigated the effect of cutting speed. This study was performed on 100Cr6 steel with a hardness of HRC 61–63. The cutting tool was a 55° diamond-shape Al_2O_3–TiC insert with −30° rake angle, 5° clearance angle and 0.8 mm nose radius. Cutting conditions were 50 μm/rev feed rate and 200 μm depth of cut. The cutting speed ranged from 0.5 to 4.5 m/s for three different levels of flank wear: 110, 210, and 300 μm. This study shows that, in general, white layer depth increases by increasing tool-wear, but not significantly at the low speed of 0.5 m/s. This increase is attributed to the associated higher cutting forces and the increased contact time. In another study, Chou and Evans [10] chose the reference cutting condition to be 3 m/s cutting speed, 50 μm/rev feed rate, 200 μm depth of cut and 300 μm flank wear land. Data points were used to represent the average values of tests, and error bars showed the ranges of values for each test. It was shown that the white layer depth also increases with cutting speed, but eventually seems to approach an asymptote at high cutting speeds. They also showed that the depth of cut does not affect the white layer depth and that there is a slight increase with feed rate. Yang et al. [9] studied the wear characteristics of the white layer using a pin-on-disc machine. As shown in Fig. 1, the thicker the white layer, the lower the wear resistance of the material. This may be due to the occurrence of micro-cracks.

Now, to specifically answer the question if the white layers are a tribological advantage or inconvenience for machining industry, the following can