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White layer formation due to phase transformation in orthogonal machining of AISI 1045 annealed steel

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Abstract

It is commonly believed that the white layer formed during machining of steels is caused primarily by a thermally induced phase transformation resulting from rapid heating and quenching. As a result, it is often assumed that if the temperature at the tool flank–workpiece interface exceeds the nominal phase transformation temperature for the steel, a white layer forms. However, no attempt has been made to actually measure the temperatures produced at the tool flank–workpiece interface and correlate it with microstructural evidence of phase transformation. This paper aims to address these limitations through suitably designed experiments and analysis. Orthogonal machining tests were performed on AISI 1045 annealed steel at different cutting speeds and tool flank wear. During machining, temperature measurements at the tool flank–workpiece interface were made using an exposed thermocouple technique. Metallographic studies of the machined sub-surface and X-ray diffraction (XRD) measurements were performed to determine the presence and depth of white layer, and the presence of the retained austenite phase in the machined surface layer, respectively. Analysis of the data shows that the white layer can form due to phase transformation at temperatures below the nominal austenitization temperature of the steel. Possible causes of this result are presented.

Keywords: White layer; Orthogonal machining; Workpiece surface temperature; Phase transformation

1. Introduction

A white layer is a featureless layer that typically forms on machined steel surfaces and appears white when observed under an optical microscope after standard metallographic preparation. It is therefore often called the white etching layer in the literature. There have been many studies about white layers generated in various manufacturing processes such as hard turning [1–5], electric discharge machining [6], reaming [7], grinding [8–10] as well as service parts such as locomotive rails [11,12] and bearings [13]. Various characteristics of the white layer have been reported [14]. It is observed not only in ferrous metals, but also in non-ferrous metals such as titanium [15] and brass [16]. However, the underlying mechanisms that give rise to the white layers are not fully understood.

Three key mechanisms responsible for white layer formation in various manufacturing processes are identified by Griffith [17] as: (1) phase transformation due to rapid heating and quenching, termed the thermal effect in this paper; (2) fine grain structure formed due to severe plastic deformation, termed the mechanical effect in this paper; and (3) reaction of the surface with the environment. In machining of steels in particular, two mechanisms, thermal and mechanical effects, are considered to be the major causes of white layer formation. Although the potential role of mechanical deformation on white layer formation in machining has been acknowledged by researchers [2–4,7,8,11–14,17], it is commonly assumed in the literature that the white layer is formed when the workpiece surface temperature exceeds the nominal phase transformation temperature, A_s (austenitization temperature), in the equilibrium Fe–C phase diagram [2,18–20].

Regarding measurement of temperatures in machining, several studies have been reported on the measurement of the tool–chip interface temperature using various methods [21–26]. In addition, efforts to use the measured temperatures to account for microstructure alteration in chips have also been reported

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Table 1
Chemical content and nominal phase transformation temperatures (A_{c1} and A_{c3}) of AISI 1045 annealed steel [33–34]

Composition (wt.%)					A_{c1} (°C)	Ac_3 (°C)
C	Mn	P	S	Fe		
0.42–0.5	0.6–0.9	0.04 Max	0.05 Max	Bal.	727	800

[27]. However, only a few attempts have been made to measure the workpiece surface temperature [28–32], and none to use the measured temperatures to account for microstructural changes in the workpiece surface. Bosheh and Mativenga [32] used the temperature of the just-machined surface measured using a pyrometer to point out one cause of white layer formation. However, no attempt was made to actually measure the temperatures produced at the tool flank–workpiece interface during cutting and correlate it with microstructural evidence of phase transformation.

Therefore, the primary objective of this paper is to experimentally investigate the workpiece surface temperature during white layer formation in machining of AISI 1045 annealed steel and correlate it with microstructural evidence of phase transformation, if any.

2. Experimental work

Orthogonal machining of AISI 1045 annealed steel is performed at different cutting speeds and flank wear levels to induce different thermal and mechanical effects on the workpiece surface. The cutting forces and temperature at the tool flank–workpiece interface are measured to quantify the mechanical and thermal effects on the workpiece. After machining, optical micrographs generated using standard metallographic techniques are used to confirm the presence/absence of white layer, and X-ray diffraction (XRD) measurements are performed to check the presence/absence of retained austenite, which serves as evidence of phase transformation. The following section presents the details of the experimental work.

2.1. Workpiece material

Annealed AISI 1045 steel is chosen as the workpiece material for this study because it does not contain any martensite or austenite prior to machining. Thus, the presence of retained austenite after machining serves as evidence of metallurgical phase transformation. The workpiece hardness was measured to be 99.1 ± 1.4 HRB using a Rockwell hardness tester. The nominal chemical content and phase transformation temperature for the steel are given in Table 1.

2.2. Machining conditions

Several cutting speeds and flank wear levels were used to induce different levels of thermal and mechanical effects on the workpiece surface. The experimental design used is given in Table 2. Note that the flank wear widths used in this study range from 100 to 600 μm. The unusually large flank wear land sizes (see Fig. 1) are necessitated by the limitations of size and fragility of the thermocouple used in the temperature measurement technique discussed in the next section of the paper.

The workpiece was in the form of a tube with outer diameter of 41 mm and a wall thickness of 1.5 mm. Kennametal NG3125L carbide (KC 730 grade) inserts with 0° rake angle tool holder (NER-163D) were used. A uniform flank wear land was generated by artificially grinding the clearance face of the tool.

Orthogonal machining was carried out with 3 mm axial length of cut under dry conditions. At the end of cut, the tool was retracted quickly using a drill pecking cycle command, G74, to minimize the effect of tool dwell on the machined surface. Preliminary tests [34] show that the dwell zone is less than 10% of the entire machined surface and hence is not significant. Cutting forces were measured with a piezoelectric force dynamometer (Kistler Model 9257B). The tool flank–workpiece surface interface temperature was measured using an exposed thermocouple technique described in the next section.

2.3. Measurement of workpiece surface temperature

The exposed thermocouple method [35] was employed to measure the workpiece surface temperature at the tool

Table 2
Experimental design

Workpiece material	Tool material	Cutting speed (m/min)	Flank wear width, VB (μm)	Feed (mm/rev)
1045 annealed steel	Carbide KC 730	100	100	0.1
		100	420	0.1
		100	600	0.1
		200	100	0.1
		200	260	0.1
		200	310	0.1