The Effect of Technological Conditions of Hard Turning on the Formation of White layer

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Abstract. In fast spreading hard turning occasionally a so-called white layer appears on the machined surface, which is mostly harmful. The formation of white layers and their composition, structure and thickness were investigated in the turning of the inner cylindrical surface of gear wheels made from 20MnCr5 case hardened steel, in order to identify to what extent the technological parameters of turning influence the white layer formation. On the basis of the measurement results it was possible to include border-line technological conditions in an empirical formula with which white layer formation can be avoided.

Introduction

In the production of parts one of the most important development tendencies of hardened steels machining in the last one or two decades has been the ever wider spread of hard turning. One negative characteristic is, however, the occurrence of a white layer. On the surface of parts that had been ground a special hard layer was evinced that resisted the etching usual in metallographical examination and stayed white in the photos [1]. From this comes its name, white layer, or White Etching Area (WEA) [2]. This can be observed first of all on hard turned surfaces (Figure 1), but it was also evinced on a worn flank surface of HSS coated with TiN (Figure 2), also reported by Veldhuis et al. [3]. The existence of a white layer is mostly harmful, because it worsens the reliability of parts, and the mounting of such parts involves risk. The reason for this is that the deformation originating from the strain of the rigid, very hard material part loaded with residual stress can be borne only to a limited extent. Through the effect of the pulling, bending, twisting strain, hair-line cracks may occur. Besides that there is the risk of chipping, which leads to ruts. The white layer is a disadvantage for the fatigue limit, as shown by the convincing data about rolling fatigue examinations of Guo et al. [4], and it also decreases resistance to stress corrosion cracks [5]. Its only advantageous feature is that it may improve wear resistance in sliding friction, according to Barry and Byrne [6].

The appearance of the white layer is the result of a peculiar process. At a given time not the whole volume of the workpiece but only a very small part heats up to the temperature at which under normal heat treatment conditions α-γ phase transition takes place in the steel, then quickly cools back to its previous temperature. The process is very fast, the speed of the heating up is 10^6 °C/s and that of the cooling down is 10^4 to 10^5 °C/s, according to Yue Caixu et al. [7].

The processes going on in the heated up particles are obstructed because of the cold material around and the pressing influence of the cutting force, that is thermal dilatation (expansion), phase transitions, plastic deformation, and recrystallization are obstructed [8]. Then this short time and obstructed process as thermal shock moving at the order of magnitude of v_c cutting speed (v_c=100…200 m/min) penetrates the surface of the whole workpiece. However, according to experience, as indicated in Figure 2 this transient thermal period is not an absolute necessary condition to create a white layer. It was able to appear on the worn flank of the tool, too, although the temperature did not fluctuate there during turning.

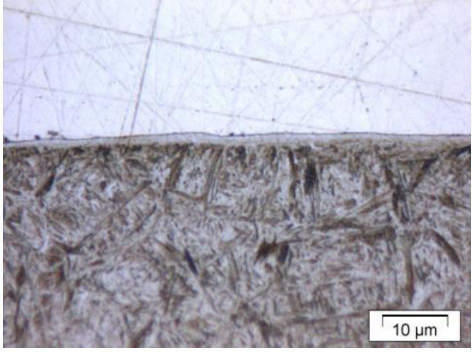

Figure 1
White layer on the hard turned surface of hardened workpiece

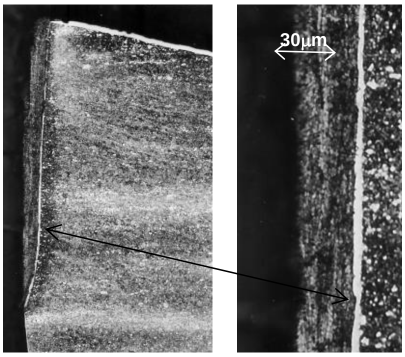

Figure 2
White layer on the worn flank of the HSS tool under the metallic build-up

As for the consistency of the white layer, there are three opinions:

a) White layer consists of untampered martensite. Martensite forms from the substance that becomes austenite because of the fast cooling down during machining. This occurs with medium or high C content [5, 6, 7]. It is true, however, that Hosseinia et al, [9], when turning martensite and bainite steel, measuring the temperature with a two-color, high speed pyrometer, stated that well before A_{c1} transition below 750 °C the white layer for, therefore at least two mechanisms must operate: during A_{c1} the white layer is formed, activated by plastic deformation, however above 900 °C it forms by a thermally activated mechanism. In the speed range of v_c=30-260m/min the appearance of the white layer was independent of the martensite or bainite state. It was also stated that in formation of a white layer, there is less residual austenite and the residual stress is negative in the surface layer. According to Brinksmeier [10] the white layer is very fine-grained martensite (α-Fe peaks) in hypo-eutectoid steel, while in hypereutectoid steel it is mainly austenite (γ-Fe peaks). Later onthis was verified by Klocke [2].
b) According to Brandt [11] and Tönshoff et al. [12] in eutectic and hypereutectic steels the white layer contains up to 73 % austenite, confirmed by Yb Guo et al. [4].
c) According to Klocke's measurements [2] the white layer on mainly steels with C content consists of fine grains of ferrite of nanometer magnitude.

According to Veldhuis et al. [3] oxygen and aluminum are enriched in a white layer, which refers to the presence of a wearing ceramic phase.

Several researchers have already dealt with the thickness of white layer. Tanaka et al. [13] examined the influence of cutting speed, the thermal conductivity of tools and the contact time of the worn tool and workpiece on thickness. They concluded that the contact temperature and time greatly influences the thickness of the white layer; moreover, in the case of CBN coated tools with good thermal conductivity white layer formation can be prevented. In recent years, besides measurements, a number of examinations have been carried out using FEM methods to determine the thickness of the white layer. Umbrello et al. [14] applied FEM method and cutting experiments in interactive way in orthogonal cutting of AISI 52100 hardened steel. With the some steel ABAQUS/Explicit software was used by Duan et al. [15] and the researchers found good agreement between the measurements and calculations. Yue Caixu et al. [7] cut Cr12MoV hardened steel with a PCBN tool and also used finite element analysis, taking tool wear into consideration. The calculations and measurements verified the statement made before that wear facilitates the white layer formation. It was found that along the flank wear of the tool, in the surface layer of the workpiece alongside, for a very short time, of order of ms (for a few microseconds), a thermal peak of up to 1000 °C may occur.

Wang et al. [16] measured the micro-hardness of the surface layer and the layer under the surface in plain milling done with different technological parameters on H13 steel by coated insert. The current temperature distribution and deformation was calculated by FEM ABAQUS/Explicit software. The micro-hardness was found to be significantly higher on the surface than inside, which refers to deformation hardening. With increased cutting speed and feed the surface micro-hardness decreased because of thermal softening. Their measurements are interesting because, although a white layer did not appear, valuable information was revealed about the subsurface. Its structure was examined with optical and electron microscope, and elongated grains were found. The thickness of the deformed layer varied between 3 and 10 μm with increasing cutting speed and feed. The results of FEM and the measurements coincided well in their case, too.

The findings of Yan et al. [17] are interesting and important from the point of view of practical technology. They proved that the formation (presence) of a white layer can be demonstrated by a non-destructive electro-chemical method, in 3.5 wt% NaCl solution, since in this solution the specimens with a white layer were susceptible to corrosion in a way different to those with no white layer.

Although several questions about the creation of thin layer have been unanswered, more and more studies have aimed to discover directly the influence of technological parameters. Reich and Moison [18] studied surface integrity on smoothing hard turning of hardened steels. Poulachon et al. [19] studied the white layer formation, paying attention to the effect of increasing flank wear on the surface integrity. The white layer formation was monitored by metallographic microscope and by SEM on chips, searching for a relationship between the chip shape and white layer formation. Cappellini et al. [20] examined white layer formation and dark layer below in orthogonal turning of AISI 512100 bearing steel, varying the cutting speed, feed and depth of cut. As they stated, these parameters and wear influence the white layer formation. Denkena et al. [21] point out that although research on the white layer is intensive, the published results are gained under very different conditions, thus their comparison is circumstantial. In their study the surface integrity is discussed as well as residual stress, roughness, micro-structure and hardness as a function of cutting speed, feed and cutting edge in ball bearings to optimize their life cycle.

Edge radius r_β has a very important role, however unfortunately its value is only rarely indicated in the literature. Schmidt deals with it in detail in [22]. For example, at r_β=35 μm there is no white layer yet, but under completely the some technological parameters and flank wear VB_c=15 μm, at r_β=75 μm it appears. This observation is of importance, because edge radius r_β varies on commercially available tools, where he found that its value is between 3 and 20 μm. The accurate recording is considered crucially important by Jeffry et al. [23]. On the basis of edge geometry they divide CBN tools into three groups:

- up-sharp edge with no facet, r_β<25 μm
- up-sharp edge with facet, r_β<50 μm
- honed edge tools with large edge radius, r_β=100–150 μm.

The influence of these technological parameters on the formation of white layer is very important for technologists. As our previous investigation demonstrates [24], in accordance with Brandt's [11] statements, the formation of white layer can be expected if the edge strain of the cutting tool, that is the friction output falling on a unit of the length of the operating edge, exceeds the value P'_α =150W/mm.

Supplements to the white layer investigation results

For investigation of white layers the inner cylindrical surface of hardened gear wheels was cut with hole diameter d_w=48 mm. The material of the gear wheels for the investigation was DIN 20MnCr5 case hardened alloy steel, the main alloying substances were 0.2 % C, 1.2 % Mn and 1.2 % Cr.

During cementation done at 900–950°C, the surface layer at the required 0.6 mm depth enriches to 0.5–0.6% C, but it may reach 0.9–1.0%. After hardening and tempering the hardness is 59–63 HRC. The machine tool was an EEN400 lathe (P=11 kW), the tool was coated with PCBN CNGA 120408 7020, γ_n=-6°, α_n=6°, κ_r=95°, r_ε=0.8 mm, facet with 0.2×(-20°) edge geometry. Technological parameters: cutting speed v_c=120 m/min, feed f=0.05–0.20 mm/rev, depth of cut a_p=0.1–0.2 mm.

The thickness of the white layer was determined by a Quantimet 500 Image Workstation and Leica picture analyzing software, measuring the layer thickness on the specimen at 40 different spots.

To determine the structure of the white layer and particularly the quantity of the residual austenite, X-ray diffraction examinations were carried out using D8 ADVANCE (BRUKER AXS). The parameters of the measurements were as follows: applied radius CoKα, λ=0.179024 mm with no monochromatization. Acceleration stress: 40KV, electron current 40 mA, cracks: primer side: Ø1 nm Monocap, secunder side: 1 mm antiscattering 0.2 mm detector blende, measured angle interval: 2Θ=45–130°; interval: Δ(2Θ)=0.1; collecting time: 60 s. See [24] for details of the X-ray diffraction examination.

The measurement results of the white layer thickness vary not only as a function of the cutting parameters, but there was uneven thickness in some cases of technological variants. On the surface with white layer there was a place of measurement where was no white layer at all. Therefore it was worth examining the relative dispersion, too, besides the average of the layer thickness. The dispersion may have several reasons: the allowance may not be even because of the changing depth of cut a_p during machining, the cutting force may fluctuate due to the inhomogeneity of material or vibration, etc.

The results of the thickness measurements obtained by analyzing the photographs are summarized in Figures 3 and 4. It was found, in accordance with the data published in the literature, that the cutting technology significantly influences the layer thickness and its relative dispersion. As a function of depth of cut the thickness of the white layer indicates a maximum (Figure 3). At smaller depths of cut the layer thickness increases, but then relative dispersity is high, close to 120 %. Contrarily at higher depth of cut (0.4 mm) the layer thickness decreases, fluctuates less, and its relative dispersion decreases to 30 %.

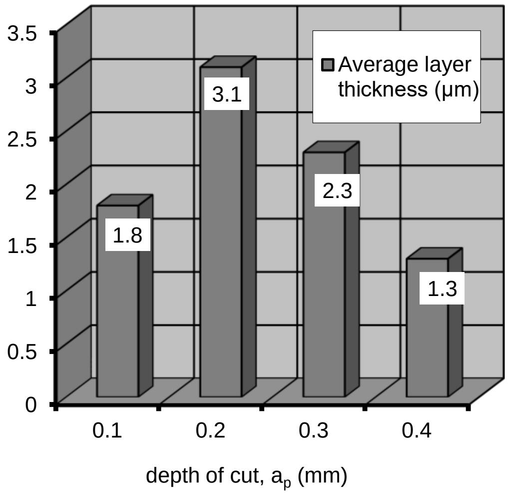

Figure 3
Average thickness of white layer as a function of depth of cut (f=0.1 mm/rev)

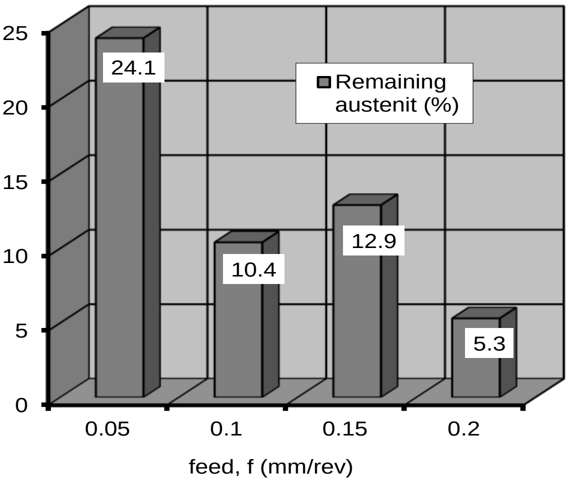

Figure 4
Amount of residual austenite as a function of feed (a_p=0.2 mm)

The X-ray diffraction examinations were carried out not only in the surface layer, but inside the sample, too, with the purpose of examining the changes there. The measurements indicated that the white layer created on 20MnCr5 steel is martensite containing 5–25% residual austenite, which is in accordance with the data in the literature [5, 23]. It also can be stated how the cutting parameters, besides thickness, influence the structure of the white layer and its environment, the amount of the residual austenite. Figures 4 illustrate the results.

The avoidance of white layer

It can be stated from the introduced measurement results in a former publication [24] that no meaningful connection was found between the thickness, structure or composition of white layer created when applying different technological parameters. The same is the case in connection with the specific friction edge output [11]: there is no meaningful relationship between the edge output and the amount of residual austenite (R^2=0.41). According to the examination results, the specific friction edge output does not reveal anything about the thickness of the creating layer or its relative dispersion (R^2≈0 and R^2≈0.35, respectively).; no meaningful relationship between them can be discovered This, of course, can be the consequence of an insufficient number of experiments for making statistically backed statements.

However, a significant, reliable result of the investigation is that it verifies Brandt's statement [11] that the white layer formation in cutting steels can be expected if on the tool flank the specific friction edge output is higher than the value of P'_α=150 W/mm. This specific friction edge output can be calculated with the formula

$$P'_\alpha = \frac{\mu \cdot \sqrt{F_p^{\,2} + F_f^{\,2}} \cdot v_c}{l_c} \text{ (W/mm)} \tag{1}$$

where F_p is passive force, F_f is feed direction force, μ is the friction factor on the flank and l_c is the length of the operating edge section, which can be calculated with

$$l_c = r_\varepsilon \left[\arccos\left(1 - \frac{a_p}{r_\varepsilon}\right) + \arcsin\frac{f}{2r_\varepsilon} \right] \tag{2}$$

if $a_p > r_\varepsilon$. Here r_ε is the rounding of radius of edge, f is feed, a_p is depth of cut.

Based on the results of the experiments outlined in the previous chapter it can be stated that the specific friction edge output really does provide an opportunity to select between technological variants as to whether they are dangerous from the point of view of white layer formation. As one can see in Figure 5, the results show a clear distinction between the white layer formation cases, indicated by filled circles, and the variants with no white layer formation, indicated by empty circles. From this an empirical function can be created that makes it possible to determine in advance whether there is the risk of white layer formation or not, if the practical technological data are available.

It is know that cutting force as a function of technological parameters can be described with the empirical formula

$$F_d = C_F \cdot v^x \cdot f^y \cdot a_p^z \tag{3}$$

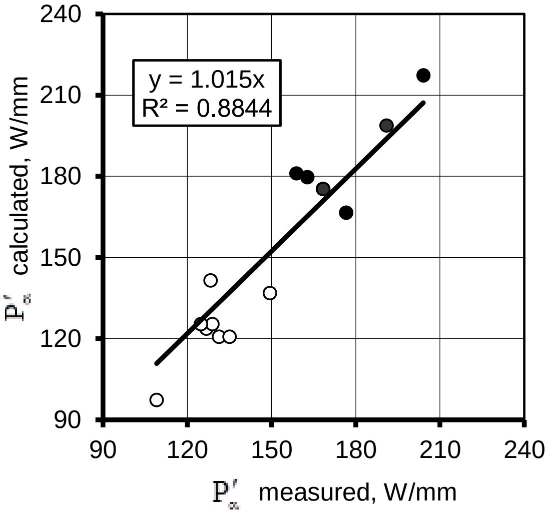

Figure 5

The matching of P'_α values (white layer shown by filled circles)

With this, and also using formulas (1) and (2), cutting speed $v_{c,max}$ can be determined, and a v_c value smaller than that has to be chosen to be sure of preventing white layer formation.

This is $v_{c,max}$ speed

$$v_c \le v_{c,max} = \left[\frac{C_x \cdot l_c(mm)}{f(mm/rev)^y \cdot a_p(mm)^z} \right]^{\frac{1}{1+x}} \tag{4}$$

where

$$C_x = \frac{150}{\mu \cdot C_F} \tag{5}$$

Constants C_F, x, y and z are generally not directly available, but one can find data regarding F_p passive force and F_f feed direction force, or they can be determined by direct measuring as a routine. Then, from the two forces the empirical function (3) can be determined. The advantage of this method is that an empirical formula can be created for calculating the specific flank friction output, too, which can be used without measuring forces in materials of that hardness in a wider range.

In this case, with the cutting parameters given in the previous section, force measurement also took place, presuming constants C_F =244.4 N, x=0.3, y=0.59, z=0.31 and μ=0.26 [11] C_x=145.5. In the case of the examined hardened steel, if white layer is to be avoided, with the allowed maximum cutting speed, r_ε=0.8 mm, resulting in

$$v_c \le \left[\frac{141.5 \cdot l_c(mm)}{f(mm/rev)^{0.31} \cdot a_p(mm)^{0.59}} \right]^{\frac{1}{1.3}} \tag{6}$$

On the basis of this formula Figure 6 was plotted indicating the allowed maximum cutting force $v_{c,max}$ as a function of feed f and depth of cut a_p if r_ε=0.8 mm.

In the case when cutting speed has been prescribed among technological data, the maximum feed allowed for white layer avoidance at different depths of cut can be calculated on the basis of formula (6), as shown in Figure 7.

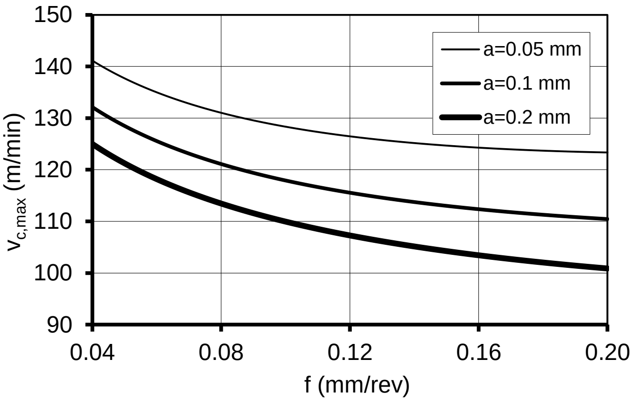

Figure 6
Allowed cutting speed $v_{c,max}$ to avoid white layer at different feed rates

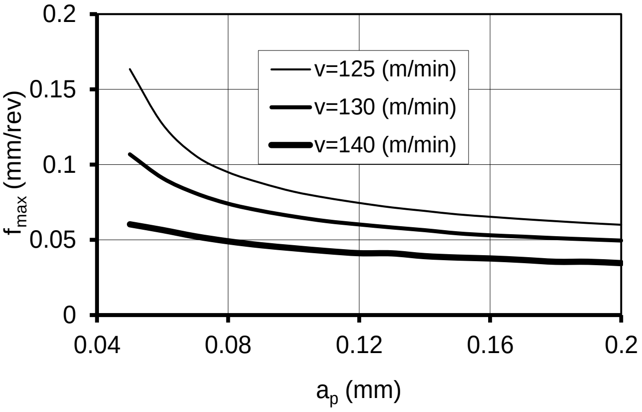

Figure 7
Allowed feed f_{max} to avoid white layer at different depths of cut

Besides the unambiguous practical value of these investigation results, it must be noted that further investigation is required for the technological application of formulas (4) and (5). Although the investigation results demonstrated in this paper proved the applicability of the μ=0.26 value, still it would be expedient to check it in other applications. On the other hand, it is true that edge radius r_β of the tool as well as its flank wear are implicitly involved in formulas (4) and (5) through forces, but it has not yet been proven that these cannot modify the 150 W/mm border value of specific friction edge output. While the border value is correct in the cases measured here, it would be desirable to confirm this in other technological applications, too.

Summary

One of the accompanying phenomena of wide-spreading hard cutting is white layer formation on the surface of the workpiece, which it is usually expedient to avoid. The aims of this paper are to contribute to the information on the formation and structure of white layer and to elaborate a technological model that makes it possible to count the cutting parameters so that white layer formation is prevented.

According to our measurements, the white layer on the 20MnCr5 case-hardened steel is martensite containing 5–25% austenite. The thickness of the white layer is dispersed greatly. The 150 W/mm specific friction edge output value on the tool flank is confirmed to be a border value (see Brandt [11]), above which white layer formation can be expected This allows us to create an empirical function/formula for calculating in advance whether there is a risk of white layer appearance, given the practical technological data. Further investigation is required for a wider technological spread of the elaborated calculation model.

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