White layer formation mechanism in dry turning hardened steel

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Abstract
The studying white layer produced in dry-hard turning process has important theoretical significance and practical value. The experiments of orthogonal turning AISI 52100 and AISI 4340 steels were employed by using PCBN inserts, a series of experimental methods were employed to study the microstructure, phase component, element segregation and hardness of machined surface. Based on experimental results, the white layer formation mechanism and the effects of cutting parameters and material properties on the white layer thickness were studied. The results show that there is ultra-fine microstructure in the white layer, the carbon segregation occurs in the machined surface and the retained austenite content is larger than that in the substrate, which indicates that the white layer is the product of phase transformation. The grains in the white layer are refined and the hardness of white layer is larger than that of the substrate, which illustrates that the plastic deformation promotes the formation of white layer. In conclusion, white layer is formed under the interaction of phase transformation and plastic deformation. The thickness and retained austenite content of white layer increase at first then decrease with cutting speed. The white layer thickness increases with feed rate, carbon content and hardness of material.

Keywords : Dry-hard turning, Steel, White layer, Formation mechanism, Cutting parameters, White layer thickness

1. Introduction

Dry-hard high speed turning has advantages in high efficiency, environmental protection and so on compared with traditional machining, so it is more and more used in machining hardened steel( Guo and Waikar, 2010; Zhang et al., 2017). However, the researches have shown that the microstructure of machined surfaces produced by dry-hard turning is different from that of substrate and the white layers can be observed under optical microscope ( Guo and Waikar, 2010; Huang et al., 2015). White layer is at top surface of machined surface, so the microstructure and formation law of white layer have great effect on performance and service life of workpiece.

The studies have been conducted on white layer formation mechanism, one viewpoint is that white layer is a product of phase transformation(Kundrák et al., 2012; Pálmai and Kundrák, 2016; Umbrello, 2013). Chou and Evans (1999) used the Al2O3-TiC ceramic tool to cut hardened AISI52100 steel, the result shows the volume fraction of austenite in the white layer is more than that in the substrate, so they consider that large amount of cutting heat generated in cutting process causes surface temperature up to austenite phase transformation temperature, then the machined surface is rapidly cooled after contacting with air and undergoes martensite transformation. Another viewpoint is that the plastic deformation is a main factor in formation process of white layer(Hosseini et al., 2015; Ranganath et al., 2009; Zhang et al., 1997). Rice et al.(1991) observed the white layer through transmission electron microscopy(TEM),the result shows that the dislocations with high density exist in the machined surface. Severe plastic deformation forms a mass of dislocation, resulting in the refinement of grain size. The third viewpoint is that the white layer is a result of combined action between cutting heat and plastic deformation(Bosheh and Mativenga, 2006; Han et al., 2008; Rancic et al., 2017). Ramesh et al.(2005) investigated the white layers at different cutting speed, they demonstrate that the white layers are produced by grain refinement caused by plastic deformation at low cutting speed, while it is produced by phase transformation induced by cutting heat when cutting speed is high. Hard turning is a process of thermal-mechanical coupling, the formation of white layer is accompanied by both cutting heat and plastic deformation, so the formation
The mechanism of white layer is still controversial.

The influence of cutting parameters on the microstructure of white layer have been held by scholars as well. Attanasio et al. (Attanasio et al., 2012; Umbrello and Rotella, 2012) analyzed the white layer of AISI52100 within the cutting speed range of 75m/min-250m/min, it indicated that the white layer thickness increases with cutting speed. The selected cutting speed in these studies are mostly concentrated in 100–350m/min, which are in low cutting speed ranges. However, with the emergence of new tool materials, higher cutting speed has been applied in hard turning process, the change rule of cutting heat at higher cutting speed is different from that at low speed, which will have different effect on the formation of white layer. Bosheh and Mativenga (2006) explored the hard turning process of H13 tool steel from low to high cutting speed, the results show that the white layer thickness decreases with cutting speed. However, the cutting speed values which were chosen in the experiments are so few that the variation of white layer thickness with cutting speed cannot be revealed accurately. Umbrello and Jawahir (2009) studied the influence of hardness on the white layer thickness of AISI 52100 by finite element simulation, the investigation illustrates that the white layer thickness increases with the hardness of substrate. Not only the hardness but also the chemical composition have influence on the microstructure of alloy that is formed under high temperature and severe plastic deformation, but the effect of chemical composition especially carbon content on the formation of white layer under the condition of thermal-mechanical coupling has not been fully discussed.

Based on the above problems, the objective of this paper is to find out the white layer formation mechanism under cutting condition of thermal-mechanical coupling and the influence rules of cutting parameters and material properties on white layer formation. The microstructure was observed through optical microscope and SEM, the phase component and retained austenite content of white layers were measured and calculated by XRD, the hardness of white layer was measured by micro-indentation test, EPMA was used to investigate the elements distribution in white layers. The white layer formation mechanism was analyzed based on experimental results, the effect of cutting parameters on white layer formation was discussed, the change trend of white layer thickness with carbon content and hardness of workpiece material was discussed as well.

2. Experiments

AISI52100 and AISI4340 steels were chosen because of their hardenability, wide application and different carbon content, the chemical composition of AISI52100 and AISI4340 steels is shown in Table 1. To study the influence rule of substrate hardness on the thickness of white layer, the AISI 52100 and AISI 4340 steels were heat treated to 60HRC, 55HRC and 50HRC. The heat treatment of AISI 52100 is heating to 850°C, holding for 2 hours, quenching in oil, then tempering at 360°C for 4 hours when the hardness is 50HRC, tempering at 280°C for 4 hours when the hardness is 55HRC and tempering at 180°C for 4 hours when the hardness is 60HRC. The heat treatment of AISI 4340 is heating to 850°C, holding for 2 hours, quenching in 10% brine, then tempering at 320°C for 2 hours when the hardness is 50HRC, tempering at 180°C for 2 hours when the hardness is 55HRC and tempering at 150°C for 2 hours when the hardness is 60HRC.

The disks made of AISI 52100 and AISI 4340 steels were used in experiments, the initial diameter of disk is Ø90mm and the thickness of disk is 2mm. In order to keep experiments stable and avoid changing samples frequently, the disks were machined on a bar. The shape of sample and the schematic diagram of experimental process are shown in Fig. 1. The rotation direction and the feed direction are shown in Fig. 1, when the tool moves along the feed direction, the workpiece surface is cut and the machined surface is formed. The cutting method is chosen to ensure that the cutting process is orthogonal cutting so as to facilitate the subsequent microscopic observations.

| Material | C   | Si  | Mn  | Cr  | Ni  | Mo  |
|----------|-----|-----|-----|-----|-----|-----|
| AISI 52100 | 0.95 | 0.23 | 0.30 | 1.50 | 0.10 | 0.002 |
| AISI 4340 | 0.40 | 0.24 | 0.53 | 0.64 | 1.25 | 0.21 |

To discuss the effect of cutting parameters on the white layer formation, the different cutting speed $v$ and feed rate $f$ were explored during experiment process. The PCBN inserts with negative rake angle ($\gamma_0$) of -10°, relief angle ($\alpha$) of 7° were employed. To improve the strength of cutting edge, the negative chamfer was selected, the length and angle of chamfer is 0.05 mm and -20°. The cutting parameters are given in Table 2.
Each disk was cut into small piece specimen after turning experiment in order to be convenient to analyze under different instruments. The specimens were observed under optical microscope and SEM, the microstructure and white layer thickness under different cutting parameters and materials were obtained. The phase composition of specimens was analyzed by XRD, the 2θ scans were carried out from 40° to 100° with a step of 0.02°. The retained austenite content in white layer was calculated based on the XRD patterns of specimens. The carbon element distribution in machined surface was analyzed by EPMA. The hardness of white layer was measured by nano-indentation hardness tester.

| Cutting speed ($v$) | 200m/min, 250m/min, 350m/min, 450m/min, 550m/min |
|---------------------|---------------------------------------------------|
| Feed rate ($f$)     | 0.1mm/rev, 0.15mm/rev, 0.2mm/rev                 |
| Workpiece material  | AISI 52100 steel, AISI 4340 steel                 |
| Hardness            | 60HRC, 55HRC, 50HRC                               |

### 3. Results and discussion

#### 3.1 Formation mechanism of white layer

AISI52100 steel with 60 HRC was chosen, the microstructure of AISI52100 steel consists of martensite, retained austenite and carbide after heat treated to 60HRC. The optical micrograph and SEM image of machined surface of AISI 52100 after turning are shown in Fig. 2. Figure 2(a) proves that the white layer is narrow and bright band, its thickness is about 5μm. The dark layer appears between the white layer and the substrate. As seen from Fig. 2(b) that the machined surface shows different microstructure from the substrate, the white layer is composed of ultrafine microstructure, the carbide particles are found in white layer as well.

XRD was used to measure the phase composition, grain size and micro-strain in the white layer. Figure 3 shows the XRD patterns of substrate and white layer of AISI52100. It can be seen that the α martensite phase peaks in the substrate are intense but the γ austenite peaks are not intense. However, for the white layer, except for peaks of martensite, the strong intensity of austenite peaks is calibrated as well. Above experimental phenomena indicate that the substrate and the white layer both consist of martensite, retained austenite and carbide, but the volume fraction of retained austenite in the white layer is larger than that in the substrate. Thus, austenite transformation occurs during the white layer formation.
As the hardness of the machined material is too high, the cutting resistance in cutting process is large enough, so the unit cutting work that is required in hard turning process is more than that in conventional turning process. Since most of the cutting work is converted into cutting heat, a lot of cutting heat can be produced in hard cutting process. Dosbaeva et al. (2015) investigated the cutting temperature in hard turning of tool steel with hardness of 52HRC, they indicated that when the cutting speed is 60m/min, the cutting temperature is 779 °C, which is higher than the austenite transformation temperature. Consequently, the cutting heat caused by hard turning process induces the austenitic transformation in the machined surface. When the cutting tool leaves the machined surface, the workpiece still rotates at high speed, and the cutting heat is rapidly taken away by air. Due to high cooling rate, the quenched martensite is formed in the machined surface and as the martensite is too late to grow up, the microstructure is fine enough. Meanwhile, large amount of austenite cannot transform into martensite under rapid quenching rate, so the austenite content in the white layer is larger than that in the substrate.

![XRD patterns](image)

Fig. 3 XRD patterns of (1) substrate and (2) white layer of AISI 52100 (60HRC, $v=350m/min$, $VB=0.1mm$, $f=0.1mm/rev$)

When plastic deformation is caused in hard turning process, the grains of machined surface can be refined and the strain can be induced inside these grains, the strain inside grain is called micro-strain. To study the degree of plastic deformation in hard turning process, the micro-strain and the average grain size of white layer and substrate were estimated by Jade software based on XRD patterns, the Williamson-Hall equation (Ahamed and Senthilkumar, 2010) is used to calculate the micro-strain and average grain size:

$$B \cos \theta = K \lambda / d_\varepsilon + 4 \varepsilon \sin \theta$$

where $B$ is the full width at half maximum (FWHM) of broadening diffraction peak, $\theta$ is Bragg angle, $K$ is constant, $\lambda$ is incident wavelength, $d_\varepsilon$ is average grain size, $\varepsilon$ is micro-strain.

| Cutting parameters | Micro-strain (%) | Average grain size (nm) |
|--------------------|------------------|------------------------|
| White layer        | 0.35             | 23                     |
| Substrate          | 0.155            | 88                     |

The estimated micro-strain and average grain size of white layer and substrate are shown in Table 3, the average grain size of the substrate is 88 nm, nevertheless, the average grain size of the white layer is 23nm, the grains in the white layer are seriously refined. The grains in white layer can be refined by rapid austenite transformation and quenching process (Wang et al., 2007), however, the nanocrystalline cannot be obtained by simple heat treatment. The researches show that the grains in the alloys can be greatly refined under high strain and strain rate (Lin et al., 2017; Sun et al., 2007). The micro-strain in the white layer is 0.35, which is larger than that in the substrate, so it can be indicated that the white layer is subjected to severe plastic deformation. The extrusion and friction between machined surface and cutting tool are intense enough in hard turning process, which lead to severe plastic deformation. The high strain and strain rate can be induced in hard turning as the result of plastic deformation, the density of dislocations in the machined surface increases sharply with the assistance of high strain and strain rate. Meanwhile, the dislocation movement can be promoted by high strain and strain rate in the machined surface. As the result of dislocation movement, the high-density dislocation walls are formed within the grains, which can subdivide the grains into subgrains (Fan et al., 2017). Based on the above discussion, it can be concluded that the white layer is induced...
by the interaction of phase transformation and plastic deformation.

Figure 4 shows the EPMA maps of the machined surface of AISI 52100, the distribution of carbon element in the machined surface is shown in Fig. 4(a). It can be seen that small amount of carbon is distributed in the white layer but the carbon content in the dark layer becomes larger, it suggests that the carbon segregation occurs in the machined surface. In order to make more detail analysis of elements segregation in the machined surface, the linear analysis of C and Cr elements is shown in Fig. 4(b), it indicates that the C and Cr content in the white layer is very little, but the content of C and Cr increases obviously at the boundary between the white layer and the dark layer. As the interstitial void in austenite is larger than that in ferrite, so the ability of carbon dissolution in austenite is stronger and the austenitizing is accompanied by the dissolution of carbide particles. When the machined surface is quenched, the carbon atoms have no time to be precipitated, so the content of C in the white layer reduces apparently. In addition, the top of dark layer is at high tempering area where the carbides can be precipitated, so the carbon segregation can be observed in the dark layer. Meanwhile, Cr is easy to combine with C to form chromium carbide during tempering process, then the chromium carbide precipitates at the top of dark layer. The segregation of C and Cr elements indicates that there is temperature gradient in the machined surface and the cutting temperature has important influence on the formation of white layer.

![EPMA maps](image1)

Fig. 4 EPMA maps (a) Distribution map of C element in the machined surface (b) linear analysis map of C and Cr elements in machined surface (AISI 52100 steel, 60HRC, v=350m/min, f=0.1mm/rev, VB=0.1mm)

![Hardness chart](image2)

Fig. 5 Hardness of white layer and substrate of AISI 52100 steel (1. Substrate, 2. White layer; v=350m/min, f=0.1mm/rev, 60HRC)

Figure 5 shows the hardness of white layer and substrate of AISI 52100, the hardness corresponding to the stable stage of curve represents the measured hardness. The variation trend of hardness shows that the white layer is hardened remarkably, the white layer hardness is greater than the hardness of the substrate. The main component of white layer is quenching martensite, the saturated carbon in martensite induces the solid solution strengthening effect, which lead to the high hardness of white layer. Meanwhile, the machined surface is extruded by the cutting tool during turning process, which causes severe plastic deformation in the machined surface. The plenty of dislocations and twin substructures in the white layer also lead to the higher hardness of white layer. Furthermore, as the grain size of the white layer is small enough, which can cause the fine grain strengthening. So, under the interaction of phase transformation and plastic deformation, the white layer hardness is
higher than the substrate hardness.

3.2 Influences of cutting parameters and material properties on white layer formation

3.2.1 Influence of cutting speed on white layer formation

Fig. 6 White layer of AISI 52100 steel at (a) \( v = 250 \text{m/min} \), (b) \( v = 350 \text{m/min} \), (c) \( v = 450 \text{m/min} \), (d) \( v = 550 \text{m/min} \) (60HRC, \( f = 0.1 \text{mm/rev} \), VB=0mm)

Fig. 7 White layer of AISI 4340 steel at (a) \( v = 250 \text{m/min} \), (b) \( v = 350 \text{m/min} \), (c) \( v = 450 \text{m/min} \), (d) \( v = 550 \text{m/min} \) (60HRC, \( f = 0.1 \text{mm/rev} \), VB=0mm)

In previous study about effect of cutting speed on white layer thickness, the cutting speed which have been chosen is mostly concentrated in low cutting speed range, so most of study results show that the white layer thickness increases with
cutting speed (Cappellini et al., 2010; Zhang et al., 2016). However, at higher cutting speed range, the flow and distribution of cutting heat is different from that in low cutting speed (Müller et al., 2004), so the variation of white layer thickness in higher cutting speed may be different from that in low cutting speed. Figures 6, 7 show SEM images of AISI52100 and AISI4340 steels with the hardness of 60 HRC at different cutting speed, the white layer is refined seriously and is hard to be etched, so the featureless microstructure in Figs. 6, 7 is white layer. Fig. 8 shows the variation of the white layer thickness at different cutting speed, combined with Fig. 6, 7 and Fig. 8, it can be seen that the critical cutting speeds exist during the turning process for both AISI52100 and AISI4340 steels. For AISI52100, the critical cutting speed is 350m/min, the thickness of white layer increases with cutting speed at the range of low speed. When cutting speed is higher than 350m/min, the thickness of white layer decreases with cutting speed. For AISI4340, the critical cutting speed is 450m/min, but the variation trend of white layer thickness of AISI4340 is same to that of AISI52100.

Fig. 8. White layer thickness of AISI 52100 and AISI 4340 at different cutting speed (60HRC, f=0.1mm/rev, VB=0mm)

There are some reasons to illustrate the change rules of white layer thickness. At low cutting speed range, the cutting heat that is induced by the friction between cutting tool and workpiece increases with cutting speed, and as the result of low cutting speed, the cutting heat has opportunity to pass into the subsurface of workpiece, the temperature of machined surface increases meanwhile. The white layer can be obtained when the temperature of machined surface attains to the austenite transformation temperature. When the tool leaves the workpiece, the temperature of machined decreases quickly, which causes the quenching process. More heat generated by high cutting speed is transferred into the subsurface of workpiece, so that the depth of austenite transformation increases and the white layer thickness increases. However, Puls et al. (2016) investigated the heat partition in dry turning, they indicated that the ratio of heat flow into the workpiece decreases with the increase of cutting speed. At the range of high cutting speed, although the amount of heat increases with cutting speed as well, the proportion of heat that is carried off by chips increases and the heat that is passed into the machined surface is not much increase. Moreover, when the workpiece is separated from the tool, the convective heat transfer between the workpiece and air is enhanced with the increase of cutting speed (Holman, 2010), the heat in the machined surface is taken away by the air quickly, so the cutting temperature of machined surface decreases with cutting speed quickly and the phase transformation area is shallower as well. In this case, the white layer thickness decreases with cutting speed.

As is obtained from the XRD experimental results that the proportion of retained austenite in the white layer is larger than that in the bulk material. The research shows that retained austenite can reduce the hardness, wear resistance and fatigue strength of machined surface (Sun et al., 2004), so the retained austenite content at different cutting speed was measured. Figure 9 shows the XRD patterns of the white layers of AISI52100 and AISI4340 steels at different cutting speed. Fig. 10 shows the retained austenite content in the white layers. The retained austenite content in the white layers is higher than that in the substrate, moreover, the maximum retained austenite content of AISI52100 is about 28% at the cutting speed of 350m/min and the maximum retained austenite content of AISI4340 is about 18% at the cutting speed of 450m/min. The amount of retained austenite increases firstly then decreases with cutting speed as well. These results are caused by the change of cutting heat in the cutting process. The cutting heat produced in the turning process increases with cutting speed, and the heat is easier to transfer into the workpiece at low speed range, so the austenization in the machined surface is more adequate. When the tool leaves the workpiece, as the result of rapid quenching process, the austenite cannot be completely converted into martensite, so the retained austenite content becomes more. At high cutting speed range, as is discussed above, more cutting heat is taken away by chips and the temperature of machined surface increases little. Moreover, as the cutting speed increases, the contact time between the tool and the workpiece is reduced, the austenitization is inadequate, which leads to the decrease of retained
austenite content.

Fig. 9 XRD patterns of white layers of (a) AISI 52100 (1. Substrate, 2. \( v = 250 \text{m/min} \), 3. \( v = 350 \text{m/min} \), 4. \( v = 550 \text{m/min} \)) and (b) AISI 4340 (1. Substrate, 2. \( v = 250 \text{m/min} \), 3. \( v = 450 \text{m/min} \), 4. \( v = 550 \text{m/min} \)\( / \text{rev}, \ VB = 0 \text{mm}, 60\text{HRC} \))

Fig. 10. Retained austenite content in white layers of AISI 52100 and AISI 4340 at different cutting speed (\( f = 0.1 \text{mm/rev}, \ VB = 0 \text{mm}, 60\text{HRC} \))

3.2.2 Influence of feed rate on white layer formation

Fig. 11. White layer thickness of AISI 52100 and AISI 4340 steels at different feed rate (55HRC; \( v = 350 \text{m/min} \); \( VB = 0 \text{mm} \))

The formation of white layer is a process of thermal-mechanical coupling and the feed rate has great influence on both cutting force and cutting heat in turning process (Hammoudi, 2015), so the effect of feed rate on the thickness of white layer is studied. Taking into account of the tool strength, the hardness of 55 HRC of AISI 52100 and AISI 4340 steels were chosen to carry out experiments to investigate the influence of feed rate on white layer formation. Figure 11 shows the white layer...
thickness at different feed rate, it is indicated that when the feed rate increases from 0.1mm/rev to 0.15mm/rev, the white layer thickness increases from 2μm to 2.2μm for AISI 52100 and increases from 1.5μm to 1.8μm for AISI 4340. However, when the feed rate increases from 0.15mm/rev to 0.2mm/rev, the white layer thickness increases to 4.3μm for AISI 52100 and to 4μm for AISI 4340, the thickness of white layer increases sharply. The reason why the thickness of white layer increases with the feed rate is that increasing feed rate can cause greater cutting heat and more severe plastic deformation. As the feed rate increases from 0.1mm/rev to 0.15mm/rev, the cutting heat produced by turning process increases, however, most of cutting heat flows away with cutting chips as well. Therefore, the cutting heat that is transferred into machined surface does not increase remarkably and the white layer thickness does not increase obviously. When the feed rate increases to 0.2mm/rev, the friction and extrusion between machined surface and cutting tool become severe, which leads to extensive plastic deformation. The cutting work that is used to overcome the plastic deformation resistance increases and the cutting heat that is converted from the cutting work increases dramatically. However, the flow of the chip is not enough to remove most of the heat, so most of cutting heat remains in the workpiece and passes to the subsurface, leading to the increase of white layer thickness. So under the interaction of plastic deformation and phase transformation, the thickness of white layer increases dramatically.

3.2.3 Influence of material properties on white layer formation

The white layer is the product of phase transformation, the researches show that the content of carbon has influence on phase transformation (Chou et al., 2009; Suikkanen et al., 2009), so the effect of carbon content on the thickness of white layer is investigated. As shown in Fig. 8, Fig. 11, the white layer thickness of AISI 52100 steel is larger than that of AISI 4340 steel when the cutting parameters and the material hardness are same. Table 1 shows the chemical composition of AISI 52100 and AISI 4340 steels, it shows that the carbon content of AISI 52100 is larger than that of AISI 4340. The results illustrate that the white layer is easier to be produced when cutting the materials with high carbon content. One reason is that high carbon content can reduce the critical cooling rate of martensite formation when carbon content is below 1%, which can improve the hardenability of materials (Simons, 1974). As the white layer is formed by quenching process, the improved hardenability means that the phase transformation depth influenced by high temperature will increase and white layer thickness will be higher. The carbon content of AISI 52100 is higher than that of AISI 4340, so at the same cutting condition, the quenching depth of AISI 52100 is deeper than that of AISI 4340, which can obtain thicker white layer. The other reason is that the total phase interface between ferrite and carbide increases with carbon content, which is beneficial to the formation of austenite (Honeycombe, 1981). The material with high carbon content is more likely to be austenitization after cutting temperature exceeds the austenitizing temperature. So that, the amount of austenite that is induced in the AISI 52100 steel is more than that in the AISI 4340 steel at the same cutting condition, and can obtain more martensite as well. Therefore, the white layer thickness of AISI 52100 steel is larger than that of AISI 4340 steel.

![Fig. 12 SEM images of machined surface of (a) AISI 52100 steel and (b) AISI 4340 steel (50HRC, v=350m/min, f=0.1mm/rev, VB=0mm)](image)

Figure 12 shows the microstructure of the machined surface of AISI 52100 and AISI 4340 steels when the hardness is 50HRC and the cutting speed is 350m/min. It can be seen from Fig. 12 that the microstructure of the machined surface is elongated along the cutting direction, which indicates that the machined surface is suffered to serious plastic deformation. However, no white layer is observed in the machined surface. The white layer thickness of AISI 52100 and AISI 4340 with different hardness is shown in Fig. 13 and Fig. 14, it indicates that even though at high cutting speed, there is almost no white layer when material hardness is 50HRC, but when the material hardness increases, the continuous white layer can be obtained in the machined surface. Moreover, the white layer thickness increases with the material hardness. With the increase of the
material hardness, the plastic resistance of the cutting process and the friction resistance between the tool and the machined surface increase (Lan and Venkatesh, 2014), so the energy that is consumed in the cutting process increases. When the hardness of workpiece is low, the cutting temperature which is transferred by the consumed energy cannot reach to the austenite transformation temperature, so although the severe plastic deformation occurs in machined surface, there is no white layer, which verifies that the white layer is formed by phase transformation primarily and the plastic deformation can promote white layer formation process. When the material hardness becomes higher, the cutting heat increases during turning process and the cutting temperature reaches to the austenite transformation temperature, which can produce thicker white layer meanwhile.

![Graph](image1)

Fig. 13 White layer thickness of AISI 52100 steel with different hardness (f=0.1mm/rev, VB=0mm)

![Graph](image2)

Fig. 14 White layer thickness of AISI 4340 steel with different hardness (f=0.1mm/rev, VB=0mm)

4. Conclusions

The microstructure and formation mechanism of white layer and the influence of cutting parameters and material properties on white layer formation in dry turning hardened steels were analyzed in this paper.

The white layers show ultra-fine microstructure, the carbide particles are distributed throughout the white and dark layers. The XRD analysis shows that the phase transformation occurs during white layer formation and the thermal effect is a main cause of white layer formation. According to the comprehensive analysis of micro-strain in white layer, it can be concluded that severe plastic deformation can produce dislocation and refinement grain which would promote white layer formation. The EPMA results suggest that the segregation of $C$ and $Cr$ elements occurs in the machined surfaces, which can also confirm the occurrence of phase transformation during turning process. It can be seen from the nano-indentation hardness analysis that the hardening occurs in the white layers, this is the result of microstructure refinement and severe plastic deformation in the white layers. A series of microscopic experiment results demonstrate that the white layer is formed under the interaction of phase transformation and plastic deformation.

The white layer thickness and the volume fraction of retained austenite in white layers increase at first then decrease with cutting speed. The white layer thickness increases with feed rate and the increasing trend is more obvious when feed rate is larger. The white layer thickness increases with carbon content and hardness of substrate materials.
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