Original Article

Toward understanding of metallurgical behaviours in dry machining of hardened steel: phase transformation and surface oxidation

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\textbf{A B S T R A C T}

Dry machining of hard-to-cut materials has been recognized as one of the most prospective manufacturing techniques, while involves complicated thermal and mechanical loadings inducing physical behaviours. Therefore, the metal-physical process associated with metallurgical behaviours may initiate due to highly coupled thermo-mechanical loads, a deep understanding of these encountered phenomena in dry machining is required. In this work, the effects of two factors (cutting speed and feed rate) on prominent material behaviours including chip characteristics, phase transformation and surface oxidation in the dry milling of hardened AISI H13 steel were investigated. A reliable finite element model with implemented user defined subroutine for phase transformation was introduced to predict serrated chip, cutting temperature, cutting forces, and phase compositions simultaneously. Dry milling experiments were carried out for validation. A good consistence concerning chip characteristics and cutting forces was achieved. In the end, X-ray photoelectron spectroscopy (XPS) analysis was utilized to establish the correlation between chip colour and cutting temperature. The obtained results show that the metallurgical behaviours appeared in dry milling is attributed to the excessive rise in cutting temperature and the maximum temperature at the tool-chip interface can be evaluated semi-quantitatively. This research lays a solid foundation for an in-depth understanding of the metal-physical phenomena occurred at cutting zones.

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1. Introduction

Due to the global limited non-renewable energy and its annual consistent growth of consumption, along with the pursuit of economy and ecology, clean and sustainable manufacturing technology has indisputably been the focus of the manufacturing research community, who aims to develop and provide effective manufacturing technique to shape the raw material into desired and finished products with least energy consumption and environmental contamination [1]. Under this background, dry machining is developed with the assistance of the advanced machine tools and upgraded cutting tool, which completely abandon using any cutting fluids towards
sustainable machining with zero emission and pollution, following the elimination of hazardous effects on environment and human health as well as the economic burden reduction of manufacturing enterprises [2]. Thus, dry machining has become the hot issue in the scientific research community, and also manufacturing industries have increasingly noted its potential broad application in products manufacturing with metals.

Although the merits of dry machining have been highlighted, the major concern associated with dry machining is mainly attributed to the excessive rise in temperature at the tool-chip interface due to the absence of cutting fluid, which causes microstructure alteration and surface oxidation at this region. Lima et al. [3] recorded the highest temperature 493°C when dry end milling of AISI D2 steel with cutting speed 180 m/min and feed rate 0.15 mm/rev. Zhang et al. [4] estimated the temperature at the tool-chip contact surface more than 1478°C exceeds austenization temperature 1010°C during hard milling of H13 steel. Based on the theoretical method for temperature prediction, Cui and Guo [5] indicated the maximum transient tool temperature was over 700°C when intermittent turning of AISI 1045 steel in dry condition. Evidently, the higher cutting temperature is one of the most significant highlights in dry machining. Further, metallurgical changes induced by elevated cutting temperature are the main concerns both for researchers and engineers, which have been proved to be directly related with fatigue life of the end-product and tool life [6]. Consequently, many researchers have made their attempts to investigate the related scientific problems with the purpose of feasible application in engineering. An accurate measurement of cutting temperature can provide in-depth clues to help reveal the material behaviours at cutting zones but still is a difficult task due to the heat generation location and the motion of the machine tools. Until now, tool/chip thermocouple, infrared pyrometer and the implanted thermocouple are commonly used temperature measurement methods [7–9]. Although several approaches have been developed, the feasibility of cutting temperature measurement and its accuracy are unsatisfactory. Furthermore, cutting temperature is a crucial factor to elaborate the complicated metal-physical phenomena including dynamic recrystallization, phase transformation and surface oxidation, encountered in dry machining. As reported by Novovic et al. [10], the elevated temperature caused by dry machining contributed to the phase transformation and microstructure change. White layer was also observed when turning of AISI 1045 steel by Han et al. [11]. It was concluded that white layer formation is the consequence of phase transformation in spite of the temperature below the theoretical phase transition temperature. Zhang and Guo [4] used the analytical and experimental methods to explain the phase transformation and oxidation in the serrated chip during dry milling of H13 steel. They stated that the cutting temperature exceeded the austenization temperature. Umbrello [12] performed dry turning experiments of Inconel 718 alloy under different cutting speeds. Higher hardness, grain refinement and phase change on the machined surface were observed. Rotella et al. [13] observed the higher β volume fraction compared with original material when dry turning of Ti6Al4V alloys, which in turn confirmed the occurrence of phase transformation. Sharma and Sidhu [14] observed higher temperature and micro-hardness when turning of AISI D2 steel in dry condition. When high speed machining of FGH95 Ni-based alloy in dry condition, the white layer was generated on the machined surface, Du et al. [15] explained that it was the consequence of the combined effects of phase transformation and plastic deformation. Although extensive work has been dedicated to studying the metallurgical change at cutting zones, only a few scholars have put the stress on phase transformation modeling in steels cutting. On another hand, scant researches can be found to reveal the correlation between chip oxidation featured with specified color and cutting temperature, since chip oxidation at high temperature is evitable.

In a nutshell, as one of the most prospective sustainable manufacturing techniques, researchers have shown their great interests in the field of dry machining with various kinds of metallic material as the experimental workpiece. Finite element method (FEM) has been widely employed as an efficient tool to model the machining process, which can help provide further insight into the metallurgical evolution in metal machining [16]. It should be highlighted that the appearance of material behaviours affecting surface properties in dry machining is the main challenge. Further, milling is one of the most widely adopted machining techniques, especially for the machining of the complex surface, which marks it out from turning due to the intermittent nature.

In this paper, experimental and finite element analyses were conducted to investigate the material behaviours (serrated chip formation, phase transformation and surface oxidation) in the dry milling of AISI H13 steel. A finite element model with implemented phase transformation sub-model was established and used to predict the cutting temperature and phase changes. Dry milling experiments were conducted to verify the developed FE model. Also, the correlation of cutting temperature and chip color was described with the assistance of the XPS characterization technique.

2. Experimental works

Hardened AISI H13 steel (50 HRC) with the chemical composition (in wt.%) of 0.320.45 C, 0.801.25 Si, 0.200.60 Mn, 4.755.5 Cr, 1.101.75 Mo, 0.801.20 V, 0.030 Ni and balanced Fe was used for cutting experiments, and its thermal and mechanical properties at room temperature are listed in Table 1.

Dry milling experiments were conducted on a DAEWO ACE-V500 vertical CNC machining center with coated indexable milling insert installed on tool holder with a diameter 20 mm. The machining experimental setup and cutting insert are shown in Fig. 1. The machining conditions adopted are given in Table 2. SEM (FEI Quanta FEG 250), XRD (DMAX-2500PC), and XPS (ESCLAB 250XI) characterization techniques were conducted to observe the microstructure changes and surface oxidation. Fig. 2 shows the schematic of milling operation and measurement areas. The data of XPS spectra were acquired using monochromatic Al Kα radiation with spot size 500 μm. The binding energy was calibrated referring to C1s signal at 284.6 eV.
Table 1 – Physical properties of AISI H13 steel at room temperature.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>7800</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>211</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.28</td>
</tr>
<tr>
<td>Hardness (HRC)</td>
<td>50 ± 1</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>1425</td>
</tr>
<tr>
<td>Area reduction (%)</td>
<td>23.0</td>
</tr>
<tr>
<td>Thermal conductivity (W/m K)</td>
<td>23.01</td>
</tr>
<tr>
<td>Specific heat (J/kg K)</td>
<td>417</td>
</tr>
</tbody>
</table>

Fig. 1 – Detailed specifications of the experimental setup and cutting insert.

Table 2 – Machining conditions for dry milling of AISI H13 steel.

<table>
<thead>
<tr>
<th>Test</th>
<th>Cutting speed v (m/min)</th>
<th>Feed per tooth fz (mm/tooth)</th>
<th>Axial depth of cut ap (mm)</th>
<th>Radial depth of cut ae (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 #</td>
<td>250</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 #</td>
<td>300</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 #</td>
<td>350</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 #</td>
<td>300</td>
<td>0.15</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>5 #</td>
<td>300</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 – Schematic of experimental procedure (a) serrated chip formation and (b) measurement areas of XRD and XPS.

3. FE modelling for hard milling of AISI H13 steel

In the cutting simulation, a thermo-mechanical coupled model was developed with commercial software Abaqus/Explicit. This model is made up of four parts: (i) cutting tool; (ii) base; (iii) joint (predefined separation path) and (iv) chip, as shown in Fig. 3. Johnson-Cook (J-C) model was used to define the material viscoplastic flow behaviour. J-C damage criterion was adopted in cutting simulation and applied to ‘joint’ part to define the separation of the chip from the workpiece, which is used to identify the material damage evolution for accurately capturing the generated serrated chip. An appropriate strain displacement was selected using a trial-and-error method to define element failure and deletion. Table 3 lists the used J-C model parameters and corresponding J-C damage parameters. The Zorev model was employed to describe the frictional interactions at workpiece-tool-chip contact surface [17]. The heat partition coefficient was set as 0.9 to describe the heat flux flows into the chip. Phase transformation kinetics combined with modified aust-
softening is limited to a narrow space. In addition, a good consistency between the predicted cutting forces and experiments was achieved, as shown in Fig. 8. The cutting forces $F_x$, $F_y$ decrease with cutting speed while increase with feed rate. This is attributed to the temperature increase with cutting speed inducing significant thermal softening as well as more mechanical work required for large feed rate to overcome shear plastic deformation [22].

Table 4 lists the detailed comparisons between the simulated and measured chip characteristics and cutting forces. The relative errors between simulation and experiment are in the range of 2.6–17.7 %, implies the established FE model used for milling of AISI H13 steel is accurate and reliable, which can be utilized for subsequent cutting temperature and phase change prediction.

4.2. Cutting temperature and phase transformations

It is known that excessive temperature is the prominent drawback of dry machining among sustainable manufacturing techniques. Behind this, deterioration of surface integrity associated with metallurgical evolution accompanying high temperature is the main concern. Machining-induced shear plastic deformation on the machined surface is fairly severe, some scholars [11,23] approved that stress and strain have a non-negligible effect on phase transformations. Fig. 9 illustrates the distributions of cutting temperature at the tool-chip interface and austenite volume fraction. In Fig. 9(a–c), the highest temperature in the secondary deformation zone was in the range of 840–1080 °C. The austenite volume fractions are depicted in Fig. 9(d–f). The austenite initially appeared in the secondary deformation zone with low cutting speed. As the cutting speed increases, the austenite gradually appeared in the primary shear zone. A higher ratio of austenite was noted in the serrated chips with higher cutting speed. Although lower cutting temperature by applying lubrication and cryogenic cooling through heat absorption and lubrication crush formation in machining has been confirmed [24,25], one interesting phenomenon should be noted that lower cutting temperature is observed in the milling process than that in turning process due to the intermittent nature of milling operation [26]. Despite the observed higher cutting temperature in the dry milling of AISI H13 steel, phase alteration was absent from machined surface. Majority of the heat over 90 % generated during the cutting process is carried away along with chips [27,28]. Heat dissipation after losing contact with the workpiece in one revolution is another explanation. In contrary, Han et al. [23] and Ramesh et al. [29] observed the retained austenite volume fraction increase with lower cutting speed compared with the milling speed adopted in this research on the machined surface in turning of AISI 1045 and AISI 52100 steel, respectively. As a potentially sustainable
manufacturing technique, it means dry milling tend to take advantage of dry turning currently.

Fig. 10 depicts the distribution of temperature and austenite volume fraction at varying feed rate. Correspondingly, the produced austenite volume fraction in the chip back surface layer was greatly affected by the temperature and showed a higher ratio up to 57.4% when \( f_z = 0.25 \) mm/tooth. As reported by Mia et al. [30], an increase in feed rate gave rise to the elevated temperature apart from cutting speed. The elevated cutting temperature with feed rate was also identified by the simulation results, as shown in Fig. 10(a-c). Furthermore, elevated temperature with feed rate through energy conversion in the secondary deformation zone penetrated deeper in the chip back surface. It was eventually contributed to the distribution of phase constituents with a high gradient, as shown in Fig. 10(d).

The validation of the phase transformation was provided by using the XRD characterization technique, included in
Fig. 7 – The width of shear band under different cutting conditions (a) cutting speed and (b) feed rate.

Fig. 8 – Comparison of the simulated cutting forces with experimental data (a) cutting speed and (b) feed rate.

Table 4 – Comparison of predicted and measured chip characteristics and cutting forces.

<table>
<thead>
<tr>
<th>Test</th>
<th>Value</th>
<th>Chip characteristics</th>
<th>Cutting forces</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Peak (µm)</td>
<td>Valley (µm)</td>
</tr>
<tr>
<td>1 #</td>
<td>Experimental</td>
<td>109.3</td>
<td>65.3</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>93.0</td>
<td>60.6</td>
</tr>
<tr>
<td></td>
<td>Relative error</td>
<td>$-14.9$</td>
<td>$-7.2$</td>
</tr>
<tr>
<td>2 #</td>
<td>Experimental</td>
<td>100.9</td>
<td>60.0</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>99.0</td>
<td>63.1</td>
</tr>
<tr>
<td></td>
<td>Relative error</td>
<td>$-1.9$</td>
<td>5.2</td>
</tr>
<tr>
<td>3 #</td>
<td>Experimental</td>
<td>94.7</td>
<td>41.3</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>90.3</td>
<td>45.1</td>
</tr>
<tr>
<td></td>
<td>Relative error</td>
<td>$-4.6$</td>
<td>9.2</td>
</tr>
<tr>
<td>4 #</td>
<td>Experimental</td>
<td>78.7</td>
<td>38.7</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>87.1</td>
<td>41.3</td>
</tr>
<tr>
<td></td>
<td>Relative error</td>
<td>10.7</td>
<td>6.7</td>
</tr>
<tr>
<td>5 #</td>
<td>Experimental</td>
<td>98.5</td>
<td>52.3</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>90.0</td>
<td>43.4</td>
</tr>
<tr>
<td></td>
<td>Relative error</td>
<td>$-8.6$</td>
<td>$-17.0$</td>
</tr>
</tbody>
</table>

Footnote: % (relative error) = (predicted value – experimental value)/experimental value * 100.

Fig. 11. The peaks matched with martensite located at 44.64°, 64.82°, and 82.32° [31] were defined for bulk material as well as for the serrated chip collected under $v_c$ =250 m/min. However, the simulation result for $v_c$ =250 m/min showed the existence of the austenite on the chip back surface. Meanwhile, a higher volume fraction of austenite with the maximum value rose from 37.68 % to 43.91 % was highlighted on the chip back surface with cutting speed. Zhang et al. [32] stated that austenite transformation could occur rapidly when the temperature reached the austenite transformation temperature. Stress-strain effects considered also facilitate the austenite transformation in a comparatively low austenitization temperature [19,24]. The diffraction peaks of the retained austenite located at 50.67° and 90.68° appeared when cutting speeds
Fig. 9 – Distributions of cutting temperature and volume fraction of austenite phase during chip formation (a) (d) 250 m/min, (b) (e) 300 m/min and (c) (f) 350 m/min. Note: SDV1 represents the volume fraction of the austenite, similarly hereinafter.

Fig. 10 – Distributions of cutting temperature and volume fraction of austenite phase during chip formation (a) (d) 0.15 mm/tooth, (b) (e) 0.20 mm/tooth and (c) (f) 0.25 mm/tooth.
were 250 m/min and 300 m/min, respectively. Referring to the integral intensity of the corresponding two peaks, the amount of the retained austenite on the chip back surfaces was minor, less than 5% in contrast with the simulation results. In reality, the retained austenite volume fraction measurement of the experimental chips was performed at room temperature after completely cooling down. The re-transformation process from generated austenite to quenched martensite at the cooling stage cannot be avoided. Most of the austenite formed during dry machining stage re-transforms back to martensite due to rapid cooling [33,34]. On the other hand, limited test areas of XRD measurement could be one of the explanations considering the non-uniform distribution of austenite. Observation shows that no retained austenite existed on the chip back surface for low cutting speed and feed rate. In conclusion, experimental results confirm the accuracy of the predicted results and reliability of the proposed phase transformation model. A full phase transformations model taking the heating and cooling stage into consideration is necessary and should be developed in the future investigation. As far as surface property is considered, dry milling can be considered as an option for sustainable machining.

4.3. Oxidation and XPS analysis of the chip back surface

During dry machining, the thermal energy up to 96% in metal cutting flows into the chip [28]. Zhang and Guo [4] pointed out that the cutting temperature reached 1478°C in the dry milling of AISI H13 steel. The high temperature-chip tends to generate oxidizing reaction with oxygen in the air. As a consequence, an oxide layer may form on the chip surface. The probability of oxidizing reaction between elements Fe and O are summarized.

\[
\begin{align*}
2Fe(s) + O_2(g) & \rightarrow 2FeO(s) \quad (3) \\
\frac{3}{2}Fe(s) + O_2(g) & \rightarrow \frac{3}{2}Fe_2O_3(s) \quad (4) \\
\frac{5}{2}Fe(s) + O_2(g) & \rightarrow \frac{5}{2}Fe_2O_3(s) \quad (5)
\end{align*}
\]

According to the degree of the oxidation, the iron oxide is proceeding in the following sequences [35].

\[
FeO \rightarrow Fe_3O_4 \rightarrow \alpha - Fe_2O_3
\]

Due to the variation of the cutting temperature, the iron oxide and its corresponding content may be discrepant. The colours of blue, black, and red are respectively corresponding to FeO, Fe3O4, and Fe2O3. The chip colours under different milling conditions vary from golden brown to blue + dark brown, as listed in Table 5. Note, the chip colour refers to the back surface colour considering the aspects of smoothness and identification.

With the assistance of the XPS characterization technique, detailed explanation for chip colour variation can be revealed. Three exemplary cases (1 #, 3 #, and 4 #) were selected referring to the demonstrated difference in colors, the XPS survey spec-

---

**Table 5 - Comparison of chip colours under different cutting conditions.**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>1 #</th>
<th>2 #</th>
<th>3 #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip morphology</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Light brown</td>
<td>Dark brown</td>
<td>Blue + purple</td>
</tr>
<tr>
<td>Test No.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chip morphology</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Golden + brown</td>
<td>Light purple</td>
<td></td>
</tr>
</tbody>
</table>
tra of the corresponding serrated chips are shown in Fig. 12. The variation in binding energy refers to different chemical elements or valences of the same element. Once the valence changes of the same element, the binding energy also change and thus lead to the shift of the XPS peak. The peak intensity reflects the concentration value of a specific element, which is an index of escaped electron counts per second. Compared with the data reported by Zhang and Guo [4], bivalent and trivalent oxide peaks of Fe appeared.

The binding energy of O1s in O2 molecule is 529.9 eV. As shown in Fig. 13, another matched peak with binding energy equal to O1s in iron oxide was noted, which identifies the appeared iron oxide on the chip back surface. The peak intensity of O1s for chips 1 #, 3 #, and 4 # were respectively 527.73, 1749.52, and 926.67 counts per second. It is due to the fact that the thickness of the oxidation layer increases causing the higher concentration level of O1s. It means the cutting temperature corresponding to the experiment 3# is the highest. Considering the fact that O1s in FeO and Fe2O3 are respectively 529.8 eV and 529.6 eV, which are too close to identify the specific chemical composition of iron oxide. Fig. 14 shows that the spectra are mainly highlighted by the observed Fe2p3/2 peaks. For experiment 3 #, two peaks were found at 710.9 eV and 710.6 eV, corresponding to the binding energy of Fe2p3/2 in Fe2O3 and Fe3O4, respectively. The intensity of Fe2O3 in the oxidation layer is higher than Fe3O4, which makes the chip color blue + purple. In contrast, one more peak was found at 709.8 eV in the spectra of Fe2p3/2 for experiments 1# and 4#, which reflects the binding energy of Fe2p3/2 in FeO. As a consequence, the appeared brown is a reflection of co-existence of FeO, Fe3O4, and Fe2O3 in the oxidation layer. As discussed above, the appeared chip color is a combination of different kinds of iron oxides with various volume fractions produced under different temperatures. Therefore, the chip color can possibly be used as an indicator of the temperature variation at the tool-chip interface. Referring to the relationship between cutting temperature and chip color [36,37], the cutting temperatures in this research are in the range of 820–960 °C. Compared with the predicted cutting temperature in the range of 840–1080 °C under the same conditions, there is a good agreement between the predicted results and the estimated data through observing chip colors. As the work done by Hosseini et al. [38], the recorded temperature using two-color pyrometer was 13% lower than the true workpiece temperature. It was concluded by Venkatesh et al. [36] and Ning et al. [37] that the chip color changes with the variation of the cutting temperature 40 °C. Hence, in practical manufacturing activity, the discrepancy can be acceptable considering measured uncertainties.

For sustainable manufacturing, the ultimate goal of applying lubrication or cooling in machining is to guarantee surface quality and acquire long tool life through reduced friction and temperature [39]. A quick and semi-quantitatively temperature evaluation without compromising much accuracy is necessary and benefits the dry machining implementation in an extensive field.

As claimed by Zhang and Guo [4], the appearance of Fe2O3 in oxidation layer was attributed to reduction reaction between Fe2O3 and H2O when a critical temperature (1478 °C) is reached during dry hard machining. The specific chemical reactions are described by Eqs. (7) and (8). Based on the analytical analysis, the temperature at the tool-chip interface exceeded 1478 °C.

$$H_2O(l) \rightarrow H_2(g) + 1/2O_2(g) \quad \quad (7)$$
3Fe₂O₃(s) + H₂(g) → 2Fe₃O₄(s) + H₂O(g) \quad (8)

As shown in Figs. 13 and 14, the intensity of O₁s and Fe₂p₉/₂ was the reflection of cutting temperature. However, according to the predicted temperature and the correlation of temperature and chip color, the temperature in the range of 860-1080 °C is below the value 1478 °C. This reveals that the reduction reaction is not possible to occur. Gibbs free energy, as an evaluation of the thermodynamic driving force, promotes the occurrence of a chemical reaction. Gibbs free energy with a negative value means that a reaction can proceed spontaneously. According to the data accessible in Lange’s Handbook of Chemistry [40], the Fe₃O₄ has the lowest Gibbs free energy in negative compared to FeO and Fe₂O₃. Therefore, further oxidation with a great tendency could proceed at a relatively higher temperature based on the initially formed FeO as expressed by Eqs. (9) and (10), which eventually lead to the formation of Fe₃O₄, even Fe₂O₃.

6FeO(s) + O₂(g) → 2s \quad (9)

4FeO(s) + O₂(g) → 2Fe₂O₃(s) \quad (10)

### 5. Conclusions

Although dry machining has been studied for manufacturing various target materials in many fields, understanding of the material behaviours during dry machining is still necessary in order to facilitate the implementation. Experimental and finite element analyses are conducted to investigate the metal-physical behaviour associated with chip characteristics, phase transformation and surface oxidation in dry milling of AISI H13 steel. It is hopeful to give some favorable clues on dry machining hardened material as a part of sustainable manufacturing activity. The main conclusions are summarized as follows:

1. The effects of cutting speed and feed rate on cutting temperature are prominent. The cutting forces are reduced with the increase of cutting speed while the opposite for feed rate. Shear band width is progressively narrowed as the cutting speed and feed rate increase.
2. As predicted, the austenite volume fraction in serrated chips increased from 25.2 % to 43.9 % with \( v_c = 250-350 \text{ m/min} \) and 10.2 % to 57.4 % with \( f_z = 0.15-0.25 \text{ mm/tooth} \), respectively. Experimental results proved the reliability of the phase transformation model. Reverse phase transformation can be reasonably assumed to occur on the cooling stage and explain the discrepancy in quantity. The machined surface is absent from austenite transformation.
3. As a consequence of oxidation induced by high cutting temperature, the chip surface exhibits specific color due to co-existence of FeO, Fe₂O₄ and Fe₂O₃.
4. Based on the correlation of chip color and temperature, the maximum cutting temperature during dry milling of hardened AISI H13 steel can be semi-qualitatively evaluated with an acceptable discrepancy.

### Conflicts of interest

The authors declare no conflicts of interest.

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